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EVALUATION OF STATE OF FINE SANDS ON THE BASIS OF SHEAR WAVE VELOCITY

M. J. LIPIŃSKI[1], M. K. WDOWSKA[2]

Abstract: The paper presents an approach to identify the state of fine sands on the basis of shear wave velocity measurement. Large body of experimental data was used to derive formulae which relate void ratio with shear wave velocity and mean effective stress for a given material. Two fine sands which contained 8 and 14% of fines were tested. The soils were tested in triaxial tests. Sands specimens were reconstituted in triaxial cell. In order to obtain predetermined void ratio values covering possible widest range of the parameter representing a very loose and dense state as well, the moist tamping method with use of undercompaction technique was adopted. Fully saturated soil underwent staged consolidation at the end of which shear wave velocity was measured. Since volume control of a specimen was enhanced by use of proximity transducers, representative 3 elements sets (i.e. void ratio e, mean effective stress p' and shear wave velocity V_S) describing state of material were obtained. Analysis of the test results revealed that relationship between shear wave velocity and mean effective stress p' can be approximated by power function in distinguished void ratio ranges. This made possible to derive formula for calculating void ratio for a given state of stress on the basis of shear wave velocity measurement. The conclusion concerning sensitivity of this approach to the fines content was presented.

Keywords: shear wave velocity, fine sands, state of soil, triaxial tests.

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1. INTRODUCTION

Measurement of body wave velocity for geotechnical purposes has become more and more popular during the last three decades. It concerns field and laboratory tests as well. There are some reasons for that. In case of field techniques, rapid progress in electronics made possible to add some additional sensors to most often used (CPTU and DMT) probes for static penetration. This enhanced interpretation capabilities of these tests. Also in hole tests like down-hole and cross-hole have become more often used for geotechnical purposes [1]. It results from a few premises. The first one results from the fact that the actual measurement refers to a very small strain range (around 10^{-4}%). Such a small strain corresponds to true elastic response of material and therefore shear wave velocity can be used to calculate initial shear modulus G_0 which is a key parameter in many geotechnical problems. The second reason of increased popularity of seismic waves velocity results from considerable progress which has been done in quality of measurement. It concerns field and laboratory techniques as well. Regarding shear wave velocity measurement in the laboratory, piezoelements embedded in top and bottom of triaxial specimen has been used in many laboratories. Bender elements are these kinds of piezoelements which are the most popular, since in cohesive materials they generate very clear signal. It should be emphasized that although in commercially available triaxial equipment one piezoelement (usually bender type) is used for generating shear and longitudinal waves, this is not the most favorable situation, with respect to P waves velocity measurement. It is better to use separate pairs of piezoelements for S and P waves. Such solution improves ability to correct identification of arriving signals. Also much experimental work has been done concerning improvement of interpretation of the data [2]. It should be also pointed out that both kinds of waves velocity can be measured at any stage of laboratory tests thus delivering additional independent measurement which enhances interpretation capability. For instance, measurement of longitudinal wave velocity during saturation stage can be used as an indicator of degree of saturation. It correlates very well with degree of saturation S_r and Skempton's parameter B. P waves were also used to evaluate porosity in different sandstone formations [3] and for identification of gas presence in clay soil pore spaces [4]. Although both kinds of waves are useful, shear waves are more often used. This is due to the fact, that shear waves are propagated through contacts of grains and particles and thus reflect changes in soil fabric, effective stress state and void ratio. The last two components constitute state of material and therefore shear wave velocity can reflect it quantitatively. Much research has been devoted to this issue [5], [6], [7], [8], [9]. Numerous formulae relating shear wave velocity and soil state have been proposed in scientific papers. Majority of these formulae concerns cohesionless soils. This is due to the fact, that mechanism of compressibility in sandy soils is more complex than in case of cohesive soils. The difference between compressibility characteristics in cohesionless and cohesive soils is shown in Fig. 1. In case of normally consolidated cohesive soils compressibility curve is unique with respect to soil kind. Any soil sample of slurry consistency if consolidated will follow the same compressibility for the first loading. In such case value of void ratio will always result only from applied stress. Entirely different situation is in cohesionless soils, which might have numerous compressibility lines, each starting from placement void ratio what is shown on the left hand side of Fig.1. Contrary to cohesive soils in case of sands it is a value of initial (placement) void ratio that subjects position of compressibility curve. Due to small compressibility of material, slope of the curve is small and therefore magnitude of stress doesn't change void ratio much, but certainly contribute to state of the material. Even more complex situation is in case of intermediate soils i.e. containing some amount of fines, which results in considerable differences in compressibility characteristics [10]. This feature creates premise to determine void ratio on the basis of shear wave velocity and state of stress components. This is very vital in some practical applications among which the most relevant is the problem of evaluation of soil state with respect to susceptibility of liquefaction.

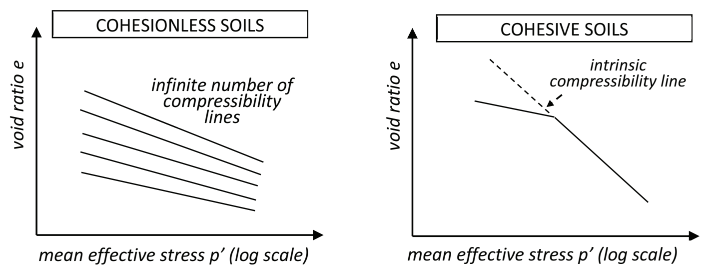

Fig. 1. The differences of compressibility characteristics between cohesive and cohesionless soils curve

Measurement of shear wave velocity in field and in the laboratory enables to use hybrid approach in evaluation of void ratio *in situ* [11]. To make this possible it is necessary to relate shear wave velocity with void ratio and state of stress for a given material. There are some formulae in the literature for selected academic sands. All aforementioned formulae are different with respect to various ways of accounting void ratio, state of effective stress and component dependent on fabric. Void ratio and state of stress component are usually expressed by power function with various exponents. There are two possibilities to account for normal effective stress i.e. to separate vertical and horizontal component of normal stress or to use mean effective stress. Some comparisons with an example shown on experimental material can be found in work [12]. The third component contributing to measured value of shear wave velocity is soil fabric. It is strictly related to method of deposition and stress history and therefore it is difficult to set representative function to reflect it. This is the reason why the derived formulae cannot predict accurately all relevant components of equation. This especially concerns void ratio which in problems associated with liquefaction is the key parameter. The issue is associated with the way of presenting the data with respect to void or shear wave velocity. The real measure of quality of derived equation should rely on the comparison of predicted and measured void ratio.

The objective of this paper is to present derivation of formulae to predict void ratio on the basis of shear wave velocity and mean effective stress for a given soil kind. In order to examine influence of fines content the research concerned two kinds of fine sands.

2. MATERIAL AND TEST PROCEDURE

As indicated, the tests were carried out on two kinds of fine sands. The first material is predominantly siliceous sand but with 8% of fines (understood as fraction finer than 0.063mm). The second material has 14% of fines which from classification point of view is above the limit to consider the material as sand. Grain size distribution of tested materials are shown in Fig. 2.

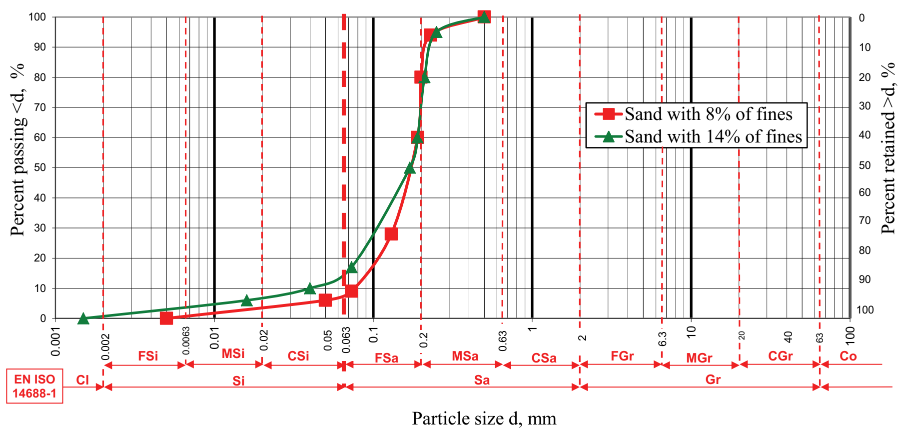

Fig. 2. Grain size distribution of tested materials

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The tests were carried out in triaxial apparatus with cell equipped with proximity transducers [13]. Triaxial tests were carried out on reconstituted specimens which were 50 mm in diameter and 100 mm in height. Specimen were prepared by moist tamping by undercompaction method as described [14]. Moist tamping was selected in order to enable preparation of samples of possible wide range of the void ratio. When a triaxial cell was assembled a specimen was flushed with CO_2 and then with deaired water. The actual saturation was achieved with application of back pressure until Skempton's parameter B exceeded value 0.96. After saturation, specimens were consolidated with application of isotropic or anisotropic stress. In case of the latter, zero lateral strain method of stress application was used. When consolidation was terminated, shear wave velocity was measured. Piezoelectric transducer of bender type was used for sending and receiving the signals.

2.1. ALGORITHM FOR DERIVATION OF FORMULAE FOR VOID RATIO CALCULATION

As it was mentioned shear wave velocity was measured at the end of each consolidation stage. Depending on the target consolidation stress preceding shearing, from 3 to 4 stages of consolidation were done in each test. For sand with 8% of fines 28 samples were tested while for material with 14% of fines 8 ones. The results for each kind of material were presented in the form of two charts:

- void ratio against shear wave velocity ($e \sim V_s$)
- shear wave velocity against mean effective stress ($V_s \sim p'$)

These data are presented in Fig. 3 and 4 respectively for fine sand with 8 and 14% of fines. As it can be deduced from the charts for each kind of material various ranges of void ratio were identified.

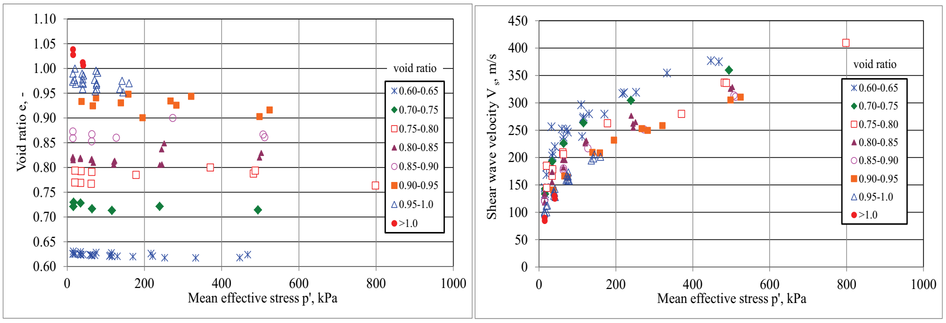

Fig. 3. Shear wave velocity measurements results in various void ratio ranges for fine sand containing 8% of fines

For sand with 8% of fines the range of void ratio 0.60-1.05 was divided into 8 subranges. It was possible only because of application of moist tamping technique during reconstruction of specimens. For very loose samples ($e > 0.9$) compressibility lines are visibly inclined. For void ratio lower than 0.9, compressibility lines are very flat, which is not the case for material with 14% of fines. For finer material the specimens were prepared as loose or medium dense therefore covering the range of void ratio 0.78-0.99. For this soil 3 subranges of void ratio were identified.

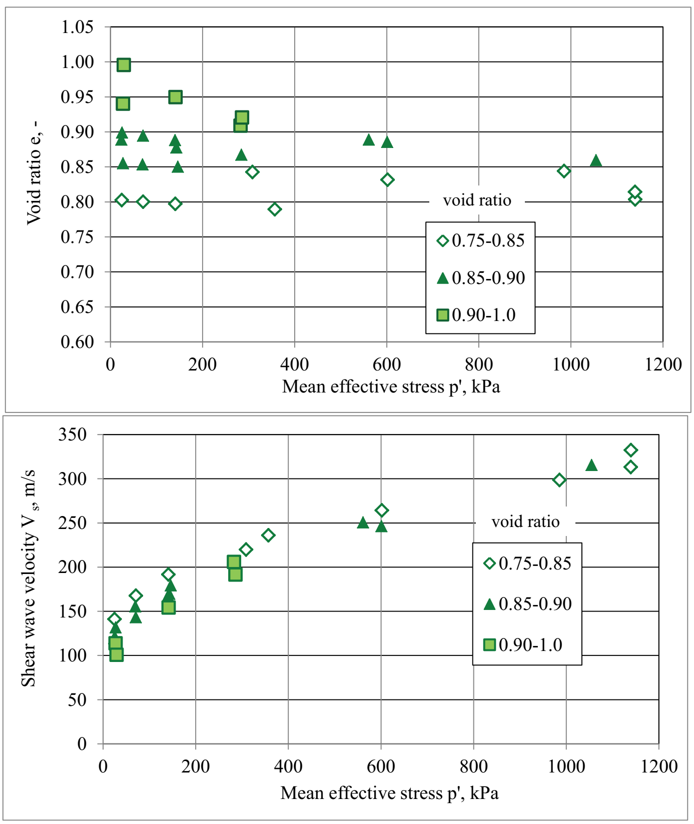

Fig. 4. Shear wave velocity measurements results in various void ratio ranges for fine sand containing 14% of fines

The division of void ratio range into subranges allowed to approximate generated shear wave velocity – mean effective stress relationship with regression curves. It is a matter of arbitrary decision what kind of function should be selected for approximation of the data. Distribution of

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points on the chart indicates that it might be power or logarithmic function. Since in work [15] logarithmic function was shown to be effective 3 kinds of different soils, for the sake of this paper power function of mean effective stress p' is assumed. The results of these approximations for tested materials are shown in Fig. 5.

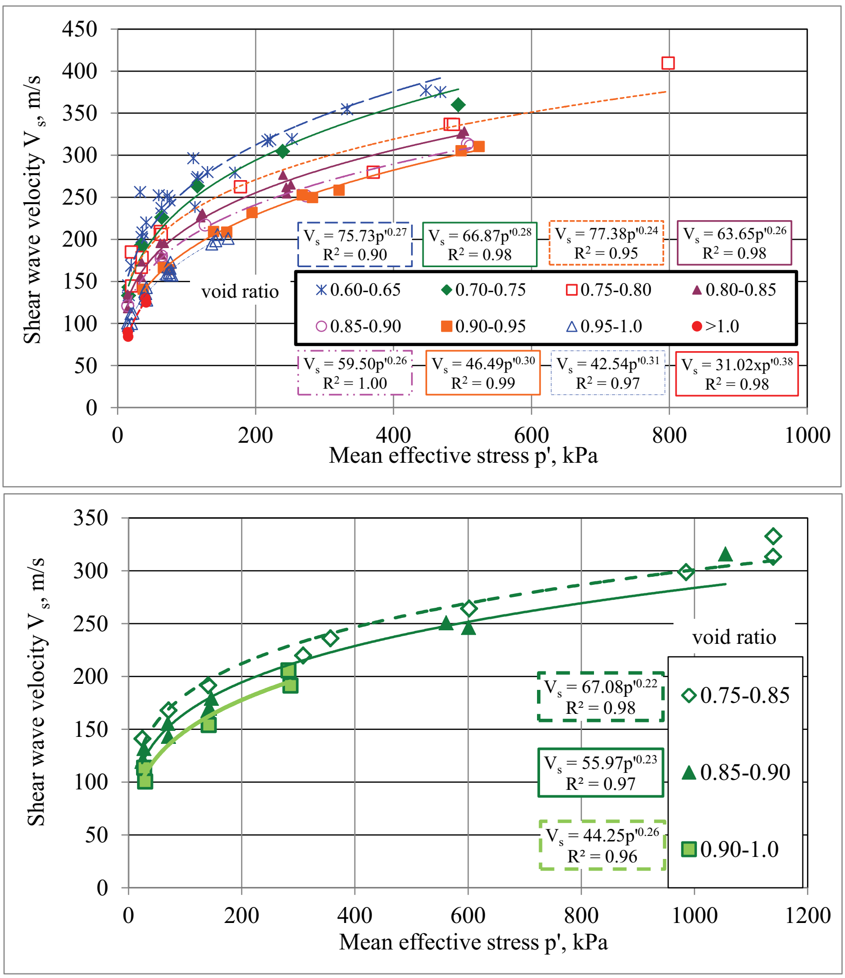

Fig. 5. Power function regressions for $V_s \sim p'$ relations for each subranges of void ratio of tested materials

As it can be deduced from the charts, the regressions reflect void ratio subranges quite well. Looking at the constants describing identified regressions it is possible to propose an algorithm for setting up formulae for calculation of void ratio for each kind of soil. The flow chart of this algorithm is shown in Fig. 6.

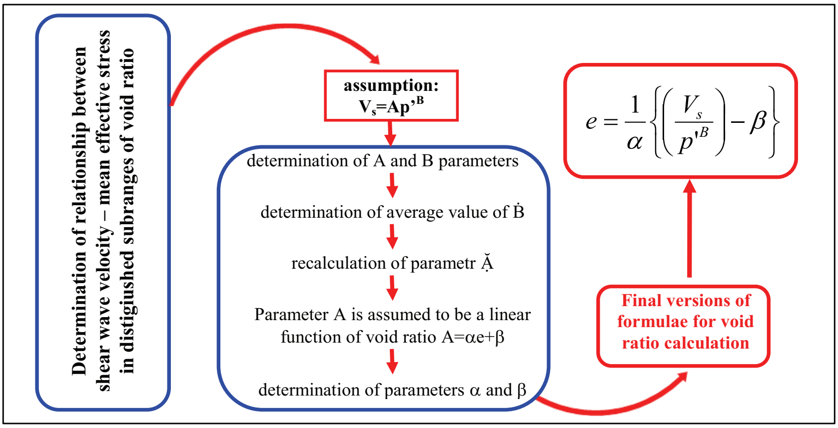

Fig. 6. The procedure for derivation of formula for void ratio calculation

The starting point for these considerations are power function regressions between shear wave velocity and mean effective stress. *A* and *B* parameters of these regressions for each subrange of void ratio are determined. Then, average value of *B* parameter is calculated. It should be pointed out that constant *A* reflects spacing between neighbour regressions, therefore *A* parameter describes change in void ratio value. To quantify this change it is assumed that parameter *A* is a linear function of void in the form $A=\alpha e+\beta$. Then, α and β parameters are determined on the basis of experimental data. As these parameters are known it is possible to derived formula for void ratio calculation on the basis of measured shear wave velocity and determined constants *B*, α and β.

3. ANALYSIS OF THE RESULTS

The above procedure has been applied to both tested materials. A chart which compares calculated against measured void ratio was assumed to be appropriate as a measure of effectiveness of the applied procedure. Such charts were prepared for both sands and shown in Fig. 7. For the sake of better comparison resulting regressions of predicted and measured values of void ratio, equal values line was drawn on each chart.

For sand with 8% of fines (Fig. 7a) the prediction of void ratio for very loose samples is very good. When material becomes denser, the formula over-predicts void ratio. For very dense material the difference between predicted and measured values is not acceptable. In spite of that R-squared is

0.88. It can be concluded that the accuracy of the method as well as its resolution is good for problems of potential liquefaction when material is not dense. A conceivable explanation might result from compressibility. Wide range of void ratio (9 subranges) creates a large potential for shear wave velocity change. In the presence of small percent of fines, change in effective stress might change also number of grains contacts, which results in shear wave velocity change.

For material with 14% of fines (Fig. 7b), comparison of calculated and measured void ratio value clearly indicates that derived formula underestimates void ratio values. For dense material it works quite fair while for loose soil is not acceptable.

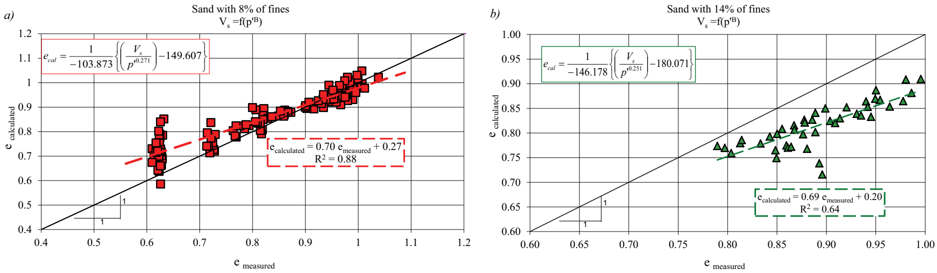

Fig. 7. Comparison of measured and calculated void ratio for fine sand containing 8% (a) and 14% (b) of fines

4. CONCLUSIONS

Shear wave velocity measured at the end of consolidation stages of samples of two fine sands containing 8 and 14% of fines allowed to formulate the following conclusions:

- Large number of shear wave velocity measurement determined for various void ratio and state of mean effective stress enable to create algorithm for derivation of formulae allowing to calculate void ratio for a given kind of soil.
- It is possible to use shear wave velocity to evaluate state of soil, however effectiveness of the power function regressions depends on the percent of fines in tested soil and on state of density as well.
- The results obtained for both sands indicate that resolution of the resulting formulae is good, however this statement can't be extended on accuracy.
- In sand with 8% of fines resolution of the method is very good but accuracy is acceptable for medium dense and loose material. This approach can be recommended for that kind of soil.

- In fine sand containing 14% of fines resolution is tolerable while accuracy is not acceptable. The derived formula under-predicts values of void ratio in the whole range of its change. At this stage of research this approach can't be recommended for material with 14% of fines.

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OKREŚLENIE STANU ZAGĘSZCZENIA PIASKÓW DROBNYCH NA PODSTAWIE PRĘDKOŚCI FALI POPRZECZNEJ

Słowa kluczowe: prędkość fali poprzecznej, piaski drobne, stan gruntu, badania trójosiowe

STRESZCZENIE:

W zastosowaniach inżynierskich często wykorzystuje się związki empiryczne pomiędzy parametrami mechanicznymi a wskaźnikami określającymi stan gruntów. O ile w przypadku gruntów spoistych prawidłowa procedura pobrania próbek lub miarodajne - spełniające odpowiednie standardy – sondowanie, zapewnia realistyczną ocenę stanu gruntu, to dla gruntów niespoistych, zwłaszcza niejednorodnych pod względem uziarnienia, problem oceny stanu jest znacznie bardziej złożony. Zasadnicza trudność polega w tym przypadku na niemożności pobrania gruntu o strukturze nienaruszonej. W tej sytuacji istnieje potrzeba poszukiwania alternatywnych sposobów oceny stanu gruntu, które pozwoliłyby na rozwiązanie przedstawionych powyżej problemów. Przedstawiona praca prezentuje takie podejście oparte na wykorzystaniu pomiaru prędkości fali poprzecznej V_S, czyli wielkości, która w największym stopniu zależy od wskaźnika porowatości i stanu naprężenia, określających stan gruntu niespoistego. Zastosowanie takiego podejścia możliwe jest dzięki zasadniczej różnicy w charakterystykach ściśliwości gruntów niespoistych i spoistych. W gruntach spoistych normalnie skonsolidowanych istnieje tylko jedna krzywa ściśliwości (materiałowa), podczas gdy w gruntach niespoistych jest ich nieskończenie wiele. Ta właściwość gruntów niespoistych stwarza przesłankę do wydzielenia wskaźnika porowatości i uzależnienia go od stanu naprężenia i prędkości fali poprzecznej.

W artykule przedstawiono wyniki realizacji doświadczalnego programu ukierunkowanego na wyprowadzenie formuły, która wiąże wartości wskaźnika porowatości, prędkości fali poprzecznej i średniego naprężenia efektywnego dla danego rodzaju gruntu. Badania przeprowadzono dla dwóch rodzajów piasku drobnego zawierającego 8 i 14% frakcji drobnej. Badania przeprowadzono w aparacie trójosiowego ściskania. Próbki gruntu były rekonstruowane w komorze aparatu trójosiowego. W celu uzyskania szerokiego zakresu wskaźnika porowatości początkowej, obejmującego stan gruntu od luźnego po bardzo zagęszczony, próbki rekonstruowano metodą ubijania wilgotnego materiału w warstwach z wykorzystaniem techniki niedogęszczania. Po całkowitym nasączeniu próbki, grunt konsolidowano etapowo. Na koniec każdego etapu wykonywano pomiary prędkości fali poprzecznej. Wykorzystanie wewnątrzkomorowego systemu do pomiaru przemieszczeń próbki umożliwiło bardzo precyzyjny pomiar zmian wskaźnika porowatości. W ten sposób otrzymano dla każdego etapu konsolidacji trójki liczb reprezentujących stan gruntu a określających wskaźnik porowatości e, prędkość fali poprzecznej V_S oraz średnie naprężenie efektywne p'. Analiza uzyskanych danych wykazała, że relacja pomiędzy prędkością fali poprzecznej a średnim naprężeniem efektywnym może być aproksymowana funkcją potęgową dla wyróżnionych zakresów wskaźnika porowatości. To pozwoliło na wyprowadzenie formuły określającej wartość wskaźnika porowatości na podstawie stanu naprężenia i prędkości fali poprzecznej. W dyskusji wyników określono wrażliwość prezentowanego podejścia na zawartość frakcji drobnej w badanych piaskach.

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