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論 文 内 容 要 旨

1. Introduction

Soil contamination is the situation where soil contains toxic substances. Among many kinds of toxic substances, toxic heavy metals are found in more than 60 volume percentage of all contaminated soil in Japan [1]. According to the Japanese law "Soil Contamination Countermeasures Act" [2], it is enacted to handle heavy metal containing soil by "containment" with "insoluble treatment". Containment is a method to isolate heavy metal containing soil from the environment. Insoluble treatment is a method to stop elution of toxic heavy metals by mixing contaminated soil with soil improvement liquid agents in mixers such as mobile soil recyclers. These two methods are economical and safe because they can be done on the site. However, operation and design of mobile soil recyclers for insoluble treatment are not optimized because the theoretical knowledge of mixing solid with liquid in mixers is not enough. Therefore, it is necessary to investigate the effect on mixing behavior by parameters related to soil, liquid and mixers.

If this investigation is carried out by experiment, it requires enormous amount of experimental material for various conditions related to soil, liquid and mixers. On the other hand, if this investigation is carried out by numerical analysis, effects of those parameters can be tested without above material. However, there is no available numerical model proper for this investigation. Then, the objective of this study is to develop a numerical model that can simulate the process of mixing a large amount of porous granular solid with a small amount of liquid in a mixer. In the future, it is desired to contribute to the optimization of operation and design of mixers for insoluble treatment through obtaining the theoretical knowledge of mixing solid with liquid in mixers by this numerical model.

Each numerical model is based on certain kind of numerical method. Because of the complexity of mixing solid with liquid, mesh-free numerical methods are expected to be suitable. In addition, the capability to handle the combination of solid and liquid was required for the numerical method. Then, smoothed particle hydrodynamics (SPH) method [3, 4] was employed judging from the previous studies [5, 6]. However, the previous numerical models had to be modified about its capability to represent the change of deformation characteristics of soil according to its water content. Then, several modification were proposed and made to describe the above behavior of soil.

2. Development of the numerical model to represent the mixing of porous granular solid and liquid

The first basic idea of SPH is "kernel approximation" to derive discretized form of function and its derivative of arbitrary continuous function $f(\boldsymbol{x})$ by using integral representation and kernel function $W(r, h)$. The second basic idea of SPH is "particle approximation" to represent the analysis object by a finite number of nodes that are called particles, which carry individual mass and occupy individual space. Then, the governing equations in continuum mechanics can be adopted in SPH numerical model.

The numerical model was developed based on the previous SPH numerical models for the combination of solid and liquid [5, 6, 7]. The governing equations for liquid are Navier-Stokes equations combined with a function to obtain known pressure [8]. The governing equations for solid are generalized Hooke's law combined with Mohr-Coulomb yield criterion. The new modifications were made on the governing equations to describe the forces that yield between porous granular solid and liquid. Those forces are seepage force, pore water pressure and suction. In the previous numerical models, there were a few problems.

The first problem is as follows. When 2 volume of liquid is mixed with 2 volume of porous granular solid that consists of 1 volume of solid and 1 volume of void, the total volume becomes 3 in realty. However, the total volume became 2 in those previous numerical models. In other words, saturated volumetric water content θ_s of soil was not properly limited by porosity of soil n. This was caused by wrong density of liquid ρ, which was obtained without concerning porosity of solid n and was used in calculation of pressure p. Then, new functions to obtain porosity of solid n around liquid and to divide density of liquid ρ by porosity n were added.

With this modification, the distribution of SPH liquid particles became more sparse. Then, the coefficient of porosity n in the function to calculate seepage force was removed to correct the magnitude of force.

The second problem is that suction is not considered. Suction is an attractive force caused by capillary action between pore in soil and liquid. This force acts in the situation where volumetric water content of soil θ is larger than 0 and smaller than porosity of soil n. Then, the proposed equations [9] to consider suction were added.

The third problem is that effective permeability K_e has not been tried in the calculation of seepage force. It is said to bring a good result in the situation where volumetric water content of soil θ is larger than 0 and smaller than porosity of soil n. Then, the proposed equations obtain the effective permeability K_e were added [10, 11].

In this chapter, four modifications were made on the numerical model to describe the behavior of mixing porous granular solid and liquid. The effects of those modifications will be validated in the following chapters.

3. Numerical analysis of seepage flow

In order to validate the modifications on the numerical model, 3 kinds of tests were carried out.

The first test was to check the numerical model about its accuracy in simulating water flow. From the result of this test, water flow was replicated by the numerical model with an error rate of 2.1%.

The second test was to check the numerical model about its accuracy in simulating seepage flow in saturated soil. This test was the falling head permeability test by JIS A 1218. In this test, the third and the fourth modifications were not applied because the soil is saturated. The accuracy was evaluated by comparing input and output parameters of absolute permeability K_0 and volumetric water content θ. The results are shown in Fig.1 and Fig.2. The results with and without modifications are marked with "Previous" and "Improved" respectively. Fig.1 shows that the first modification properly limited saturated volumetric water content θ_s to porosity of solid with the maximum error of 4.4%. Fig.2 shows that the second modification compensated the side effect of the first modification on the seepage force. In this case, the maximum error rate of absolute permeability K_0 was 26.1%.

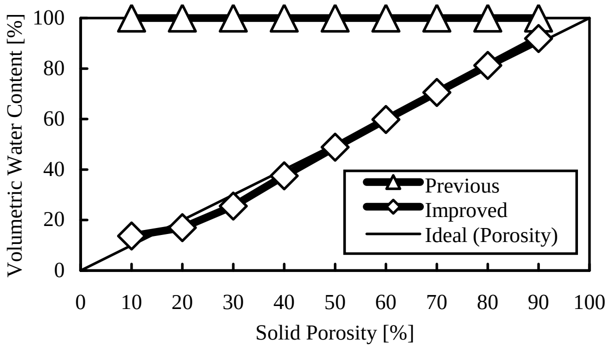

Fig.1 Validation on volumetric water content.

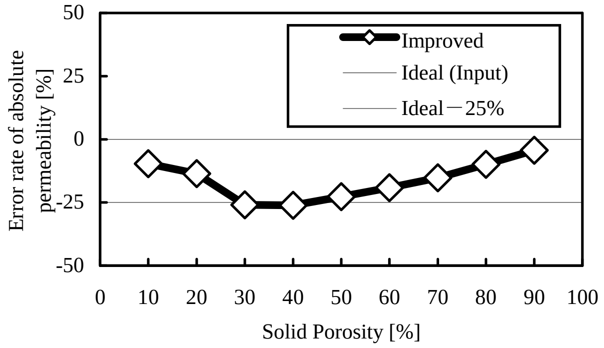

Fig.2 Validation on absolute permeability.

The third test was to check the numerical model about its accuracy in simulating seepage flow in soil with dynamically changing water content. This test was an observation of almost one-dimensional water absorption by dry soil in a transparent tube. The dry soil silica sand No.9 was set at the lower part and water was set at the upper part of the tube respectively. After water is released, top and bottom positions of it were recorded. This test was performed in the experiment and four simulations with and without suction and effective permeability K_e. The results are shown in Fig.3 and Fig.4. The results with absolute permeability K_0, effective permeability K_e and suction are marked with "Absolute", "Effective" and "+ Suction" respectively. According to results with absolute permeability K_0, it can be said that the third modification of suction improved the numerical result by 20.33% and 76.83% about the average velocity of water top and bottom respectively. On the other hand, results with effective permeability K_e were different from the experimental result. Then, it can be said that the fourth modification was not suitable for this numerical model. The reason is expected that effective permeablity K_e is not a parameter that simply represents the drag between single fluid phase and solid phase contrary to absolute permeability K_0.

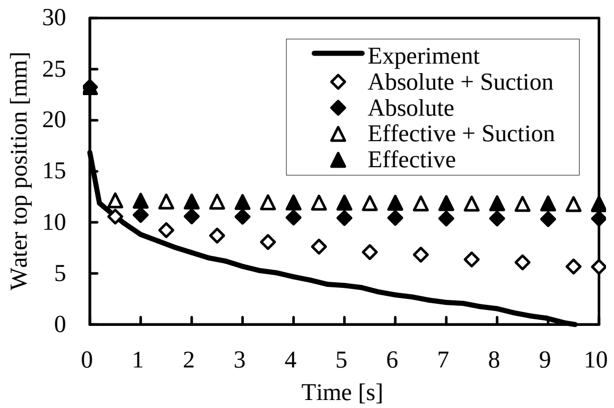

Fig.3 The change of water top postion.

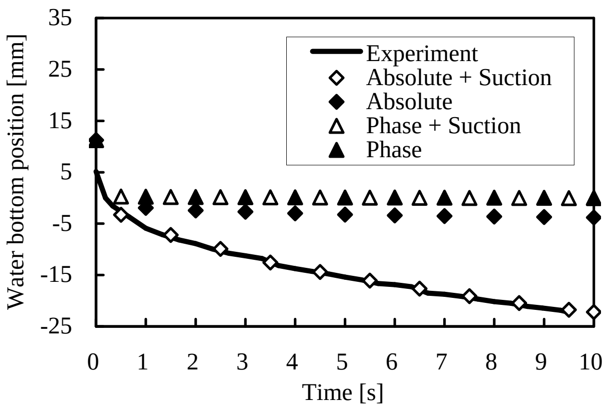

Fig.4 The change of water bottom postion.

4. Numerical analysis of mixing solid with liquid

In chapter 3, the four modifications on the numerical model about the forces that yield between porous solid and liquid were validated. In this chapter, the numerical model is validated about its accuracy in simulating mixing of unsaturated soil and liquid in a mixer.

Fig.5 shows the mixing chamber of the mixer with rotating shaft with paddles. Only right half part of the mixer was used. The unsaturated soil was 2.7 kg of silica sand No.9 with 20 weight percentage water content. The liquid was made of 50 ml of purified water and 6.25 ml of fountain pen blue ink. The unsaturated soil was initially put into the mixing chamber without compaction. Finally, the soil surface was above the shaft by a few millimeters. The liquid was dropped at the position indicated by the orange arrow in Fig.5 for 10 seconds. The shaft was rotated for 20 seconds. Rotation of the shaft and dropping the liquid were started simultaneously.

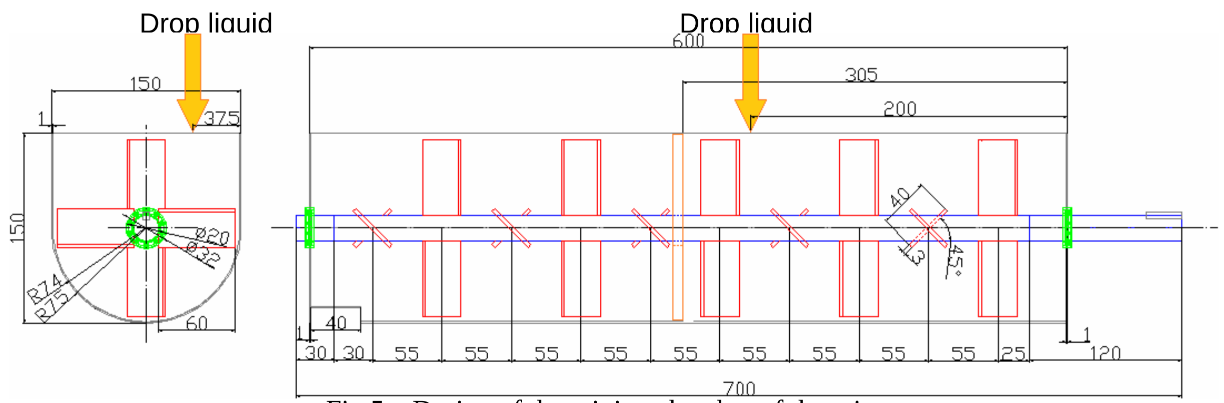

Fig.5 Design of the mixing chamber of the mixer.

After mixing, the mixture of the unsaturated soil and the liquid was obtained. Firstly, the soil above the shaft was removed. Secondly, it was divided into upper layer and lower layer. Thirdly, upper layer and lower layer were divided into 20 and 40 parts respectively. Fourthly, water content of each part was obtained. Finally, the distribution of water content obtained by the experiment and the numerical analysis were compared.

The result showed that the numerical model represented the distribution of water content with an average error rate of 21.52%. In upper layer, the maximum error rate was 18.41% and error rates were less than 12.5% at 15 points out of 20 points. In lower layer, the maximum error rate was 109.8% and error rates were less than 25% ad 24 points out of 40 points. Therefore, it can be said that accuracy of the numerical model about mixing soil with liquid is preliminary and can be improved by further modifications.

5. Conclusions

It is desired to reduce costs of "Insoluble treatment" for heavy metal containing soil. To achieve this target, it is required to optimize operation and design of mixers for mixing soil with liquid agent based on theoretical knowledge of it. Therefore, a numerical model for mixing of granular porous solid and liquid in a mixer was developed based on Smoothed Particle Hydrodynamics (SPH) method [3, 4] and previous studies [5, 6, 7]. Firstly, the numerical model analyzed a liquid flow with an error rate of 2.1%. Secondly, it analyzed a seepage flow in saturated with error rates of 4.4% and 26.1% about saturated volumetric water content and absolute permeability respectively. Thirdly, it analyzed a water absorption by dry silica sand No.9 with error rates of 9.92%-47.34% about velocity of water. Finally, it analyzed mixing of unsaturated silica sand No.9 and water with an average error rate of 21.52% about water content of 60 points in processed soil. In the future, this numerical model will contribute to optimization of operation and design of mixers for insoluble treatment with further improvement.

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（別紙）

論文審査結果の要旨及びその担当者

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論　文　題　目	SPH(Smoothed Particle Hydrodyanmics)法に基づく固液混合シミュレーションに関する研究
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論文審査結果の要旨

土壌汚染対策法では，原則的に「原位置封じ込め」と「不溶化処理」によりこれを無害化するが，不溶化処理は，土壌中の重金属等を水に溶出しにくい形態に転換する対策技術である．具体的には，汚染土壌と薬剤を混合機により混合する技術であるが，費用や安全性の面から，汚染土壌を現場から搬出せずに，現場内で処理することが望ましい．そのため，現場に搬入できる混合機として自走式土質改良機が用いられる．しかしながら，その設計と操業は経験に頼るものであり，理論に基づく最適化が望まれている．本論文は汚染土壌と薬剤溶液の混合の最適条件を理論的に把握するため，大量の固体と少量の液体を機械的な要素により混合する過程としての固液混合過程を再現する数値モデルを開発し，その妥当性について検討したもので，全5章からなる．

第1章は序論である．

第 2 章では，固液混合過程を再現するための新しい数値モデルを開発している．既往の数値モデルでは，土の含水状態による強度変化が表現されず，固体の間隙にある液体の分布の取り扱いが不正確であった．そこで，間隙にある液体の密度を補正する式，土の含水状態による浸透抵抗力を変化させる「有効浸透率」の式，固体と液体の間に働く毛管力である「サクション」の式を組み込んだ新しい数値モデルを導出した．

第 3 章では，本論文で開発した数値モデルの妥当性を検証している．まず，液体の挙動について実験結果と数値解析結果を比較検討し，容器内で流動する液体の水位変動を誤差率 2%で表現できることを確認した．次に，間隙率が 10~90%の飽和土での液体浸透に関する数値解析結果について検討し，浸透抵抗力を最大誤差率 26.1%，飽和体積含水率を最大誤差 4.4%で表現できることを確認した．さらに乾燥砂への液体浸透に関する実験結果と数値解析結果について比較検討した．これにより，有効浸透率ではなく絶対浸透率を用い，サクションを採用すると，乾燥土に浸透する液体の上端と下端の速度について，誤差率がそれぞれ 47%と 10%に改善されることを示した．間隙を含む固体と液体を粒子により表現する数値モデルにおいて，体積含水率を間隙率により制限し，有効浸透率とサクションの効果について検討したのは，本論文が初めてである．本成果は，変形する土における液体分布と浸透流れ，土の含水状態による強度変化を再現する数値モデルの開発に寄与する有益な知見を与えている．

第 4 章では，本論文で開発した数値モデルの固液混合過程に関する妥当性について検証している．実験では，不飽和土と水溶液を混合機により混合し，混合後の土における含水比の分布を求めた．数値解析では，この実験を模擬し，さらに検証のために，実験結果と数値解析結果を比較検討した．含水比についての誤差率は，上側領域で最大 18.4%，下側領域で最大 109.8%，全体平均 21.5%であった．混合機の壁面に沿う領域では誤差が大きく，課題が残るものの，本論文で開発した数値モデルは，混合機の壁面に沿う領域以外における固体と液体の混合では，妥当な数値解析結果をもたらすと推察された．混合機における固体と液体の混合について，間隙を含む固体と液体を粒子により表現する数値モデルにより数値解析を行い，その妥当性を検証したのは，本論文が初めてである．本成果は，汚染土壌処理などの固液混合過程を再現する数値モデルの開発に大きく寄与すると判断される．

第5章は結論である．

以上要するに，本論文は，固液混合に関する新しい数値モデルを開発し，そのモデルを用いて固液混合過程を理論的に解析したものである．その結果，これまでは経験的に行っていた汚染土壌と薬剤溶液の混合処理に対して，最適操業条件を理論的に把握できる可能性を示したものであり，環境科学の発展に寄与するところがすくなくない．

よって，本論文は博士(環境科学)の学位論文として合格と認める．