Geoenvironmental Disasters

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Grasp and evaluation of the unsaturated seepage behavior of soil by using MRI

Hiroaki Fujimori, Kohei Araki*, Keiichi Masutani, Hiroshi Kumagai, Hajime Sakamoto and Hiroshi Onishi

Abstract

Background: It is essential for residents to understand ground disaster and improve disaster prevention awareness, because natural disasters have occurred frequently in recent years. In this study, nondestructive unsaturated seepage behavior was continuously visualized by using MRI (magnetic resonance imaging) with test equipment constructed of non-metal parts. Additionally, the water content of the soil from the MRI image was evaluated, the results of previous experiments were considered and compared.

Results: The study revealed from the imaging with MRI that seepage will flow faster in the lower part of the cylinder than in the upper part. A discontinuous water content ratio change of the seepage line part was confirmed from image with the MRI. There was a tendency for air to be trapped on the border of different soil materials in an acrylic cylinder. It was possible for the water content of the sand in the cylinder to be evaluated from the MRI image.

Conclusions: The study suggests that complicated unsaturated seepage behavior can be easily visualized. It was suggested that air may be trapped in the different layer border of soil. And these finding will lead to the elucidation of relevance of slope collapse and the piping phenomenon with the rainfall.

Keywords: MRI, Unsaturated soil, Visualization, Seepage, Water retentivity, Moisture profile

Background

There is a very high uncertainty in predicting future ground disasters with rainfall and elucidation of the relationship between the slope collapse and piping phenomenon has been required (Araki et al. 2005; Iwami et al. 2013; Okumura et al. 2013; Araki et al. 2014; Araki et al. 2015; Yasufuku et al. 2015). In order to increase the interest of residents in ground engineering, there is a need for a visually-intuitive evaluation method of the ground. Furthermore, not only the numerical evaluation of the state of the ground by visualization is possible, but visual confirmation can also be performed at the same time. In this way new knowledge will be obtained about complicated seepage behavior of unsaturated ground. Visualization of the internal structure of the soil was carried out mainly using X-ray micro CT (Watanabe et al. 2015). The measurement method of the water contents in the ground using gamma rays has been studied by Kono et al. (1981). An MRI (magnetic resonance imaging) is used for the discovery the lesions in the medical field, and images of the inside of the human body can be directly obtained in a non-destructive manner. Moreover, the device can continue photographing for a long time. In this study, non-destructive unsaturated seepage behavior was continuously visualized by using MRI with test equipment constructed of non-metal parts. Additionally, the water content of the soil from the MRI image was evaluated, and the results of previous experiments were considered and compared.

Methods/Experimental

It is very useful if the unsaturated horizontal seepage behavior in the ground and the grasp of the water movement can visualize. A horizontal seepage examination device is used for detecting the water diffusivity by using the Boltzmann conversion method of Bruce and Klute (1956). The unsaturated horizontal seepage test equipment for MRI is shown in Fig. 1, and the schematic diagram is shown in Fig. 2 respectively. The examination equipment is constructed of ring cells with a thickness of 10 mm and a diameter of 30 mm, and the constant

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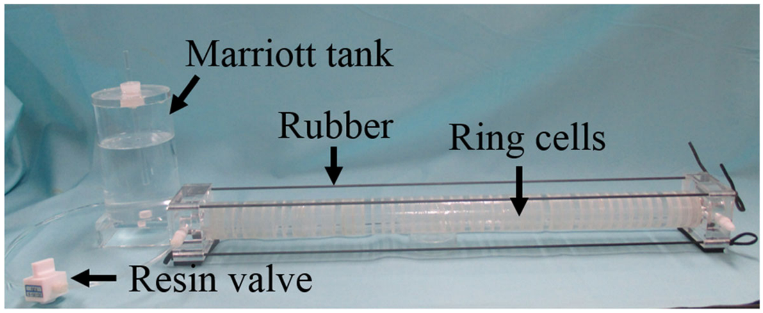

Fig. 1 Unsaturated seepage examination device for MRI

level water supply device consisted of a Marriott tank. The MRI test equipment used is constructed of non-metal parts. Dry soil is densely packed in the ring cell, and the cell is fixed with tape and rubber. The resin valve is opened and seepage starts.

Figure 3 shows how to install the test column in MRI. The test column is placed on a medical bed similar to the case of a person receiving medical treatment. During the test, it is necessary to cover the column with a plastic bag in order to prevent soil and water from scattering. The diameter of the cylinder has to be shorter than the round space of MRI.

Results and Discussion

Observation of unsaturated seepage behavior

Unsaturated seepage examination was carried out by using MRI. The MRI photography results of horizontal seepage examination using dry Toyoura sand are shown. The absorbing water process is shown at intervals of 50, 231, 531, and 920 seconds in Fig. 4a, b, c, d. Water is supplied at the left edge and spreads to the right edge. Measuring the time for the examination begins when the resin valve is opened. The high-water-content part is shown as a whiter image. Laboratory dishes with an outside diameter of 50.7 mm (and an inside diameter of 47.4 mm, and a height of 14.1 mm) are placed under the ring cells, to measure the sample water content (w = 25%, 20%, 15%, 10% and 7.5%). The soil that was adjusted for each water content is filled in those dishes. These are used as an index for estimating the water content of the sample by MRI. For photographing in the MRI device, iron sand must be removed from the Toyoura sand (approximately 0.4% overall at mass ratio). The dry density is around 1.6 mg/mm^3. At this time, the dry density of the sand in the laboratory dishes should be of the same value. Hardly any image appears when the water content is less than 10%.

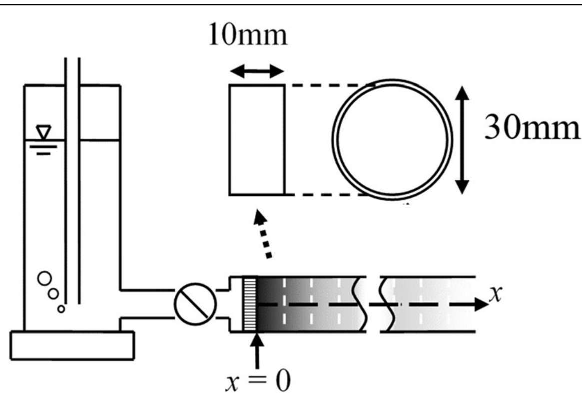

Fig. 2 Pattern diagram of unsaturated seepage examination device for MRI

The seepage proceeds approximately perpendicular for a short time after the start of the water supply, but over time, becomes faster in the lower part of two cylinder than in the upper part. These can be confirmed from Fig. 4. It is revealed that the water movement is affected by gravity even with 30 mm differences in height. There is a clearer white and black boundary in the area of the seepage front. Hereafter, this boundary will be called the seepage line. It can be confirmed that a seepage line is a disturbance (Fig. 4c). It is suggested that discontinuous water content change occurs on the seepage line. There is a black circle in the cylinder around 210 mm position (Fig. 4d). This is considered an air trap.

The MRI photography results are shown by horizontal seepage examination after packing Kaolin clay into the right part of the cylinder and Toyoura sand into the left part. The absorbing water process is shown at intervals of 735, 1185 and 3654 seconds (Fig. 5a, b, c) and the cross-sectional imaging result is shown 5072 seconds later around the 193 mm point (Fig. 6).The laboratory dishes filled with Kaolin clay over the acrylic cylinder with a water content of 50, 35, 25% are shown on the left. The laboratory dishes filled with Toyoura sand under the acrylic cylinder a water contents of 25, 15, 10% are shown on the left in Fig. 5.

Fig. 3 MRI with the test equipment. **a** The test equipment on medical bed. **b** During the test. **c** After the test

It is confirmed that seepage advances from the bottom as in the case of the cylinder filled with only Toyoura sand (Fig. 5a). The seepage line is almost orthogonal to the penetration direction when the seepage line reaches the Kaolin clay, and, it can be confirmed that the seepage front line of the Toyoura sand and the Kaolin clay are in a similar position (Fig. 5b). In the wetting process, it is because the seepage speed through the Toyoura sand layer is equal to that through the Kaolin clay layer. In addition, a black part can be identified on a border of the Kaolin clay and the Toyoura standard sand. As seen from Fig. 5c) it can be confirmed that the light and shade are not a uniform border of the left side and the bottom of the Kaolin clay and the Toyoura sand. The seepage line moves to the bottom before it reaches the Kaolin clay. It is shown that the moisture holding ability of the Kaolin clay is very much greater than that of the Toyoura sand.

As can be seen from Fig. 6, a black part towards lower left direction on a border of the Kaolin clay and the Toyoura sand. This seems to be an air trap, and the possibility that such an air trap occurs between materials of different quality of soil.

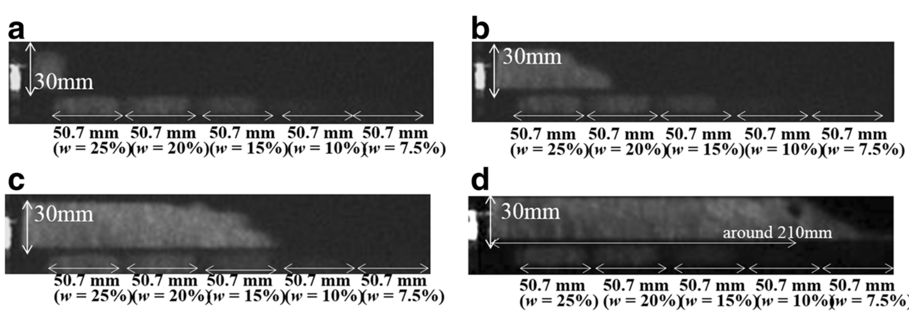

Fig. 4 Vertical section view (Toyoura sand) **a** 50 seconds later. **b** 231 seconds later. **c** 531 seconds later. **d** 920 seconds later

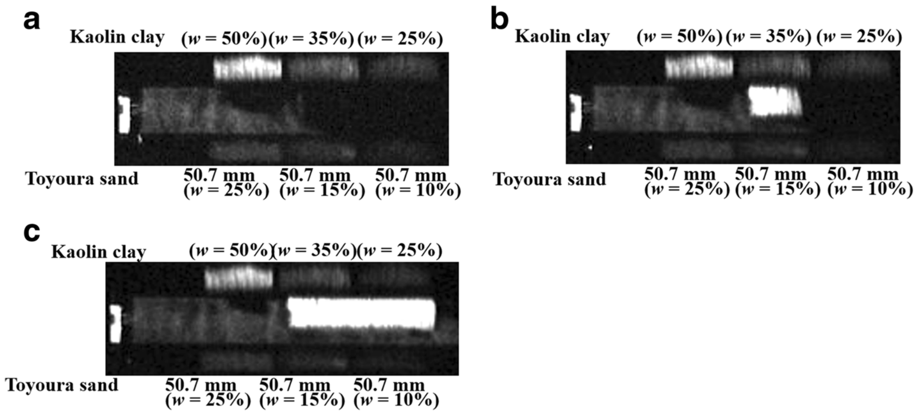

Fig. 5 Vertical section view (Toyoura sand). **a** 735 seconds later. **b** 1185 seconds later. **c** 3654 seconds later

Water content estimation of the sample by MRI

It is extremely useful if the seepage behavior from a MRI image can be evaluated continuously and in a non-destructive manner. It was shown that the logarithm approximation curve and the water content adjustment were the highest numbers of the pixel level of the laboratory dish on the cylinder in Fig. 7. Because the correlation coefficient R^2 had a value of around 0.9, which is a high value, there is a high correlation between the pixel value and the water content. It should be noted that the water content was 0 but the pixel value of the MRI image was not 0, so a logarithm approximations was used.

Figure 8 shows the water contents vs the distance in the Toyoura sand. The water contents were evaluated from the MRI image and a laboratory test (Araki et al. 2011) (Hereafter, the indicative method) respectively. In the MRI method, the water contents were evaluated from the average of the vertical section. As can be seen there is an excellent agreement between the MRI method and the indicative method.

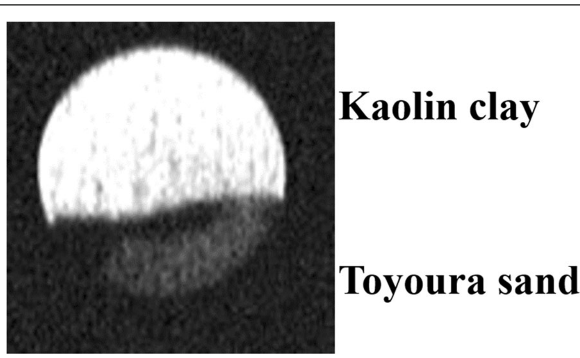

Fig. 6 Cross section view, x = around 193 mm (Upper Kaolin clay, Lower Toyoura sand)

An evaluation of the unsaturated seepage behavior by the MRI method is shown in Fig. 9. These calculation results of the Fig. 9 from Fig 4a, b, c, d respectively. It was possible to evaluate the water content and distance relations continuously by using the MRI method. It was confirmed about the water content that the seepage time increases at the same distance (Fig. 9). The water content of the part which is near to the water supply section was evaluated as having a small value, in the water content and distance at 50 seconds later. It is thought that this is affected by the boundary conditions. The seepage line reaches the position of approximately 25 mm 50 seconds later, the position of approximately 90 mm 231 seconds later, the position of approximately 180 mm 531 seconds later, the position of approximately 250 mm 920 seconds later. It is

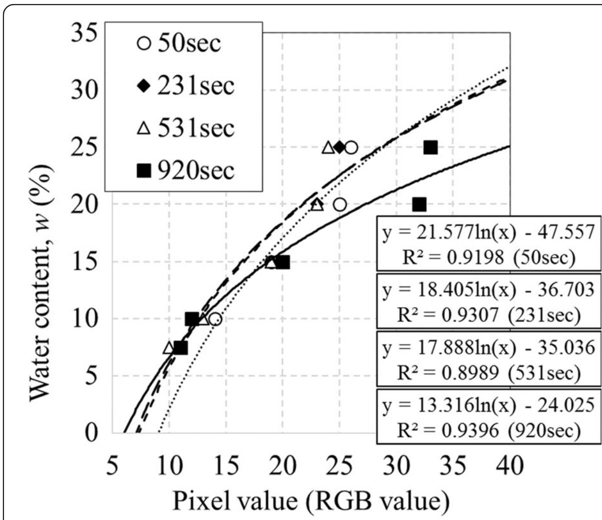

Fig. 7 Conversion from the pixel value to water content

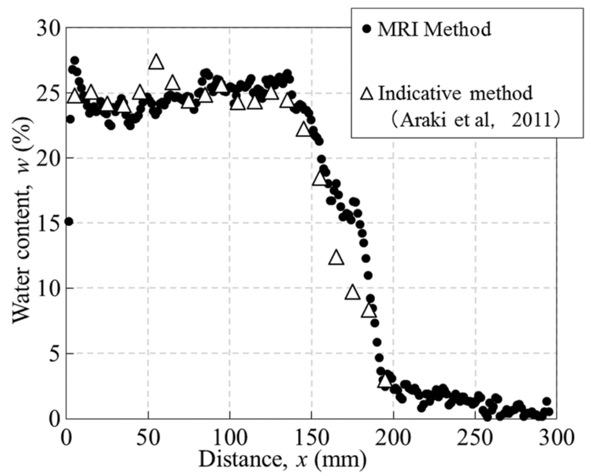

Fig. 8 Comparison of MRI method and the indicative method

understood that it becomes difficult for the seepage line to go ahead as time passes. All water content tends to decrease when it passes a certain spot. It is estimated that the air trap of Fig. 4d, produces the low water content part at 210 mm 920 seconds later as shown in Fig. 9.

Conclusion

The study suggests that complicated unsaturated seepage behavior can be easily visualized. A grasp and evaluation of the unsaturated seepage behavior was examined using an MRI device used for medical care. In this study, Toyoura sand was packed in an acrylic cylinder and the unsaturated horizontal seepage test was examined and imaged using an MRI device. A discontinuous water content change of the part of seepage line was confirmed. It was confirmed that there was a tendency for air to be trapped on the border of different soil materials in an acrylic cylinder. This study examined a technique to evaluate water content from an MRI image. These findings will lead to the elucidation of the relevance of slope collapse and the piping phenomenon with the rainfall.

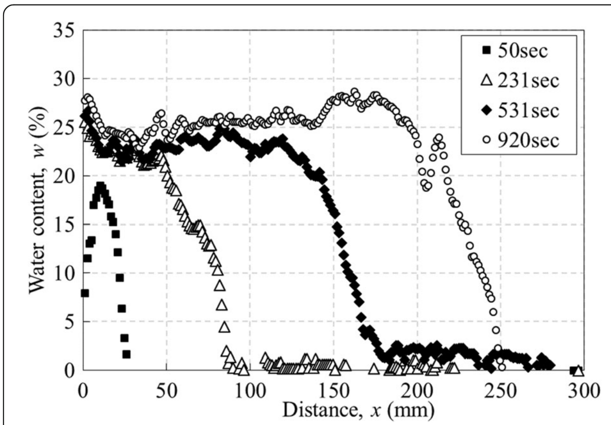

Fig. 9 Evaluation of the unsaturated seepage behavior by MRI

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Authors' contributions

HF collected and assembled data. KA designed drafting and conception of the study. KM participated in its design and coordination and helped to draft the manuscript. HF, KA, KM and HO carried out analysis and interpretation of data of MRI. HF, HK and HS performed experiment and created figures. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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