Mechanisms of Crack Formation in Clayey Paddy Fields

−The Effects of Farming on the Formation and Geometry of Cracks−

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Summary

Rotational cultivation of wetland rice and upland crops in paddy fields is common in Asian countries. In clayey paddies, however, the deterioration of drainage efficiency and soil structure during the rice cropping period remains a problem to be solved. In humid regions, the intentional improvement of drainage efficiency is essential for the cultivation of upland crops in clayey paddies. In clayey puddled paddy fields, cracks form easily due to desiccation, and they play an important role in the drainage of excess water. Thus, management of cracking in fields under rice cultivation is beneficial. Research into crack formation in soil and the resultant geometry has been encouraged by both scientific interests and the needs of both agriculture and civil engineering. Geologists have focused on mud cracks not affected by vegetation and have tried to simulate the formation of geometric patterns. However, the phenomena of cracking and of crack patterns have not been completely elucidated because of the unexpected heterogeneity governing the progress of cracking. Agronomists have focused on the cracks occurring in fields under cultivation. While many researchers have pointed out the relationship between cultivation of a field and the formation of cracks, the mechanism underlying crack formation has not been successfully analyzed from a theoretical point of view. This study aimed to clarify the factors affecting crack formation in clayey paddy fields and to elucidate the mechanisms underlying cracking from a physical standpoint.

First, in order to clarify the effects of farming on crack geometry, an experiment based on the experimental design theory was performed in a clayey paddy field during the cultivation of wetland rice. The soil was clayey, montomorillonitic, mesic, typic Epiaquepts, and contained 34-38% clay. The factors and levels to be assigned to the experimental field were 1) transpiration from rice (allowed or not allowed) , 2) row spacing (30 cm or 60 cm), and 3) puddling intensity (light, medium, or heavy). From May through July, the field was submerged. The surface water was released in August in order to induce cracks. The cracks that appeared between rows of rice plants were traced onto transparent seats, and their geometrical patterns were quantified through an image analyzing procedure. The following indices were proposed to quantify the peculiar crack geometries in inter-row spaces: '*CDI*' (Crack Directional Index) for the mean direction of cracks with respect to rows, '*EW*' (Equivalent Width) for the mean width of cracks, and '*CP*' (Compactness) for the complexity of the crack geometry. Analysis of variance (ANOVA) for each index led statistically to the following conclusions. 1) Transpiration from rice plants in rows induces linear cracks running parallel to the rows. 2) Widening the space between rows increases the mean width of cracks. 3) Intense puddling induces wide linear cracks and simplifies the cracking geometry.

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Secondly, a numerical model and laboratory experiments were used to analyze the mechanism by which the transpiration from row-planted rice induces linear inter-row cracks. The shrinkage behavior of clayey puddled soil, which can be regarded as the consolidation of saturated soil subject to negative pore water pressure, was simulated by a numerical model based on the 2-dimensional elastic consolidation theory. The model, which was developed for this experiment, describes how row-planted crops' absorption of water induces the water's bidirectional movement, and it predicts the deformation of the soil and the distribution of effective stress. The model requires parameters to specify mechanical and hydraulic properties of the soil. These parameters can be determined from the *e-log p* (void ratio and mean stress) relationship and the *e-log k* (void ratio and saturated hydraulic conductivity) relationship. The calculations were performed using the finite element method (FEM). The validity of the model was verified by the results of laboratory experiments that modeled the phenomenon observed between the inter-row spaces. These experiments were conducted as follows. An acrylic rectangular container, with sides made of a porous filter, was filled with a paste of clayey soil. The moisture in the soil was extracted horizontally from the filters by a constant suction. The water suction in the soil was measured with porous cups connected to pressure transducers. The formation of cracks was recorded by tracing the surfaces of the soil sample. This revealed the occurrence of cracks induced by bidirectional water movement, as well as the correspondence between the locations of cracks and the predicted distribution of tensile effective stress. Thus, it is proved that linear inter-row cracks inevitably occur following the balance of increasing total tensile stress and suction. Further numerical simulations demonstrated that the distribution of tensile effective stress has either single or double peaks, depending on the condition. Greater transpiration flux, wider row spacing, and a thinner layer of puddled soil induce the double-peaked distribution of tensile effective stress. This phenomenon may correspond to the field observation that the linear inter-row cracks running parallel to the rows are single at the row spacing of 60 cm, but double at the 90 cm row spacing. These issues suggest an upper limit of row spacing that is effective for enlarging the widths of linear inter-row cracks.

Thirdly, the relationship between puddling intensity and the resulting shrinkage characteristics was examined. This experiment was performed in a clayey paddy field. A randomized block design was used to carry out the experiment. Puddling intensity was examined as a unique factor. Three levels of puddling intensity - light (puddling once), medium (puddling three times), and heavy (puddling five times) - were examined in nine plots, three plots per level. From each plot, disturbed and undisturbed soil samples were taken twice: just after the puddling and three months after the puddling. A large volume of disturbed soil was sampled by inserting a plastic cylinder (diameter 20 cm, length 30 cm) into the puddled soil layer and then raking out the soil to a depth of 0-10 cm by hand. At each sampling, three replicates were taken from each plot. One of the replicates was used to determine soil water content; the others were used to quantify the amount of clods remaining in the puddled soil. A quarter of a sample (approximately 1.5 kg of wet sample) was poured into a nest of three circular sieves, each with a diameter of 200 mm and openings of 40 mm, 20 mm, and 10 mm, respectively. The sample material remaining on each sieve was scoured with tap water at a constant flow rate and from a constant height. Each clod that had not broken apart after 10 seconds of squirting was placed in a small disposable bag made of aluminum foil. The water content and weight of each of these clods was then measured. The clods with less than 80% water content by weight were regarded as 'clods remaining after puddling'. The undisturbed samples were taken from 0-4 cm and 5-9 cm layers with cylindrical samplers that were 11.3 cm in diameter and 4 cm thick. The moisture in the undisturbed samples was extracted in a pressure chamber at backpressures of 3.1 kPa, 9.8 kPa, and 98 kPa, and the weight and volume of the samples were measured at each step. Just after puddling, the puddling intensity significantly affected the content of remaining clods. Three months after puddling, while the content of remaining clods decreased in all cases, the difference due to puddling intensity still remained. Puddling intensity also affected the water retention characteristics of the puddled soil. The effects varied between the soil layers and among the suction ranges. In the subsurface layer, puddling intensity was seen to have an effect on short-term phenomena, such as the fragmentation of large clods and hardening due to kneading. Throughout the suction range, the amount of retained water increased as the intensity of puddling increased. In the surface layer, puddling intensity was seen to have an effect on long-term phenomena, such as physico-chemical changes due to reduced conditions. Intense puddling enhanced the increment of water retained after three months in a submerged condition. The difference in the air-filled void ratio after the dehydration treatments was not revealed except at the surface layer just after puddling. This result suggests that the expected difference in the fragility of the samples against the tensile stress generated by desiccation cannot be revealed by the condition imposed in the laboratory experiment. Puddling intensity also made little difference to the areal ratios of cracks as estimated from the measured shrinkage characteristics. This estimation corresponded with the field observation. In conclusion, the important properties that control the variation in cracking geometry due to puddling intensity are derived from subtle differences in the variation in the mechanical properties of the puddled soil; these properties cannot be sensed by the shrinkage test for core samples. While the content of remaining clods does not substantially affect the water retention characteristics, it does reflect the difference in soil structure that determines crack geometry.

The results of this study are expected to provide an abundance of information useful for practicing crack management. Especially, the procedure to induce wide, straight cracks can be applied directly in order to lead surface water smoothly into under-drainage systems installed in paddy fields. However, further corroborative field studies will be of great importance to the development of techniques effective for the management of clayey paddy fields and for the stable cultivation of crops.