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論　文　要　旨

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論文題名　Evaluation of Soil-Atmosphere Interaction during Evaporation Process
(蒸発過程における土と大気の相互作用の評価に関する研究)

論　文　内　容　の　要　旨

Nowadays, desertification is one of the world's most alarming global environmental problems. It takes place worldwide in drylands that occupy 41% of earth's land area. The total area affected by desertification is between 6 and 12 million square kilometers, a billion people are under threat from further desertification.

With the knowledge that only environmentally friendly engineering can provide sustainable solutions for combating desertification, the concept of "self-watering system (SWS)" has been proposed from geotechnical view, which aims to develop the greening system without any irrigation as a countermeasure of desertification. In the research program of SWS, geotechnical approach has been dedicated to development of safe and long-term water supply in arid and semi-arid region.

Some important criteria are critical to assess the performance of SWS, such as conservation of soil water, water use efficiency, and water content distribution. All these criteria are highly related to the soil-atmosphere interaction. Since evaporation is extremely high and greatly exceeding the annual precipitation in arid and semi-arid region, the evaluation of evaporation process is highlighted. However, little attention was taken from geotechnical researchers to deal evaporation process. From academic point of view, mechanism of soil surface evaporation is not completely understood, it has been a challenge for reasonably determining soil surface evaporation. In laboratory measurement, the apparatus capable of truly replicate climate characteristics to evaluate soil evaporation process is really rare.

The objective of this study is to investigate the soil-atmosphere interaction during evaporation process under saturated and unsaturated condition. The mechanism of soil evaporation is studied from both experimental and analytical approaches. In this thesis, a newly developed climate control apparatus is introduce which is characterized by the comprehensive maintenance of relative humidity, wind speed and temperature. An empirical methodology for determining soil surface evaporation is presented, which provides an estimation in high accuracy while only three easily obtained parameters are needed. The analytical model is developed for simulating water content at any time and any soil depth during evaporation process. Finally, the in-situ soil-atmosphere interaction is investigated by a lysimeter test, which also provides a practical foundation for designing the SWS. This dissertation consists of seven chapters; the specific content of each chapter is described as follows:

Chapter 1 familiarizes the readers with the concept of SWS to combat desertification. It is illustrated that the necessity of the investigation of evaporative flux for evaluating SWS in arid and semi-arid region and other typical problems. The objectives of the thesis to accomplish are briefly outlined. In addition, the original contributions are indicated.

Chapter 2 provides a brief summary of the previous research on the evaporation topics. It reviews from three aspects that are experimental approach for measuring evaporation, methods to compute evaporation and the simulation of soil moisture change. The available information is used to set the stage for further theoretical and experimental evaluation in this research program.

Chapter 3 mainly focuses on the development of laboratory test program. A newly developed climate control apparatus is put forward, which can maintain the atmosphere conditions comprehensively to investigate evaporation behavior. The apparatus is composed of climate control part, evaporation part and data acquisition system. It has the features of flexibly configuring for specimen, accuracy increased and automatic control and visualization. The calibration tests show that the apparatus is capable to favorably control wind speed and relative humidity, while temperature is stable with a relatively small range.

Chapter 4 presents the methodology for calculating soil surface evaporation. Based on the newly developed apparatus, a series of tests are carried out to investigate the influence of factors on pan soil evaporation. It is found that a linear correlation exists between evaporation rate and wind speed. piecewise linear relation between relative humidity and evaporation rate is observed with the cut off point at about 60%. Pan soil evaporation rates are almost same even for different dry densities of soil. Soil in greater particle size shows longer time of constant evaporation rate stage. From theoretical derivations of both aerodynamic approach and molecular physics approach, it is indicated that the water content alone cannot be the independent variable, to calculate the evaporation rate from all soil surfaces. Based on a newly defined parameter, critical water content θ_c, the methodology for calculating soil surface evaporation is presented, in addition, the empirical formulation of θ_c is set up for different soil textures and wind speeds. Three easily measured indexes are the inputs in this model: the moisture of top 1cm soil, aerodynamic resistance (wind speed), and field capacity as a constant for specified soil texture. Although this methodology is in empirical form, it provides high agreement between estimation and measurement of soil surface evaporation rate.

Chapter 5 develops an analytical model for simulating the temporal and spatial change of soil water content during evaporation process. Based on several assumptions, analytical solutions of Richards' equation are derived in two categories, which are one dimensional evaporation problems with or without water table. Two groups of column soil evaporation tests are conducted to verify the proposed model, the first group controls the environmental conditions without water supply while the second group controls the water table. The good agreement between the proposed analytical solution and experimental result indicates that the analytical model provides a reliable way to investigate water content redistribution during evaporation process. Finally, the parameter study is performed based on the analytical model, which includes hydraulic parameters, surface evaporative flux, and depth of water table. Some new findings are stated as well in this chapter.

Chapter 6 highlights the in-situ evaluation of soil-atmosphere interaction. The thermal and hydrological phenomena of soil are discussed based on a lysimeter test lasted for 81 days. Finite element simulation is performed to compare with the measured data. The summary are remarked that the most significant variation of volumetric water content is the near surface area, which is limited in top 35 cm; the lower the soil depth, the greater change in water content responding to evaporation or precipitation. Soil temperature at all the depths is affected by climate change. The rainfall event shows the function of eliminating temperature gradient and unifying the water content profile, while the evaporation process enlarges the gradient of temperature and water content. The comparison between measured data and simulated result indicates that numerical approach provides a rough simulation of the variation of water content and soil temperature. Further effort is required on dealing with the upper boundary.

Chapter 7 concludes the results and achievements of the whole thesis; Also, it indicates the problems to be solved in future studies.