Dependency of conservation conditions of Takase stone Buddha, Oita, Japan, on anisotropy of liquid water diffusivity

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Abstract. Takase Stone Buddhas is one of the important old stone buddha sculptures curved into the inner wall of a cave in Oita, Japan. It is located in the cave curved into the cliff of a hill of volcanic tuff. In general, because the cave is currently protected from rain and direct solar radiation by the roof shelter and waterproof treatment, the Buddhas is well conserved and no currently ongoing weathering can be clearly observed. However, because of a high ground water level, there is a concern in the influence of water evaporation at and near the surface of the stone buddhas and the wall of the cave on their deterioration. In the past, we conducted a long-term field survey of conservation environment to obtain yearly data set of the conservation environment that can be used as input of numerical simulations of heat and water transport in the material. In this paper, we report measurement data of the ground water level as well as the liquid water diffusivity of the tuff stone that significantly affects the conservation condition. We also performed numerical analyses on heat and moisture transport in the tuff stone layer and stone buddhas. The simulation results show that the conservation condition of Takase stone Buddha strongly depends on the anisotropy of liquid water diffusivity of the tuff stone.

1. Introduction
Takase stone Buddhas [1,2] is considered to have been created in the late 12th century and is one of the important old stone Buddha sculptures in Oita, Japan. It was curved into the inner wall of the cave that was curved into the cliff of a hill and has been an object of worship of Buddhism for local people. The cliff of 4 m height above the ground and its underground layer consist of tuff stone rock layers that seem to have anisotropic material properties such as the density and liquid water diffusivity. The cave has a dimension of 4.4 m x 2.3 m x 1.5 m and is 1.3 m high above the ground. The Buddhas consists of five Buddha sculptures, each of which is unique in its shape and the surface color of painting, although it is not completely known if the color of the sculpture surfaces is original or not. In 2015, the construction of a roof shelter and a waterproof treatment on the top of the cliff to reduce the influence of rain and solar radiation on the Buddhas was conducted and the Buddhas has been in general rather well conserved, while there remain a few questions in the conservation condition. First, the ground water might influence...
the conservation condition, as the water level values measured around there are not so low [2,3]. Second, the roof shelter and waterproof treatment do not only protect the Buddhas from rain and solar radiation but also restrict water evaporation from the top surface. As a result, reduced evaporation there can increase water evaporation from the surface in the cave and may cause deterioration of the surface of the Buddhas.

2. Numerical analysis
Numerical analyses were formulated to understand the conservation conditions of the Buddha. The heat and moisture transfer in the tuff stone layer were simulated using a yearly weather data set and measured material properties for moisture transfer.

2.1. Conditions
We conducted a long-term field survey of conservation environment at a location in front of the east-facing opening of the cave (see figure 1) during May 20, 2016 - May 19, 2017 [3]. The measurement data set includes the air temperature, relative humidity, horizontal rainfall intensity, solar radiation, wind speed and direction, and ground water level. The ground water level measured at two locations of two holes (see figure 1) is compared to the rainfall intensity in figure 2. The water level is the height above the altitude of 15.0 m. The floor level of the cave is at the altitude of 21.64 m.

The water retention curve and liquid water diffusivity of tuff stone taken near the cave were measured using the constant volume method, the evaporation method [4] and the Boltzmann transformation method [5]. For the Boltzmann transformation, the X-ray CT machine of Kindai University was used, which was reported in [6]. The obtained liquid water diffusivity for the horizontal and vertical directions is shown in figure 3. These material properties were used for two-dimensional numerical analyses of three cases which were conducted on the vertical section of the cliff (see figure 4) for the same period as the meteorological observation starting at May 20. In the first case (case 1), the anisotropy of the liquid water diffusivity was taken into account; in the other two cases, the diffusivity was assumed to be isotropic and the same as the value for the horizontal direction (case 2) or the vertical direction (case 3). The other detailed conditions are kept the same as [3].

2.2. Results
The spatial distribution of the saturation degree of April 18, 2017 is given in figure 5. Comparison of case 1 to the other two cases showed that the saturation distribution strongly depends on the anisotropy
of liquid water diffusivity of the tuff stone. On the other hand, comparison between case 2 and case 3 also shows that the results are not influenced by the value of the diffusivity so much.

3. Conclusions
The numerical simulation results showed that the saturation degree in the tuff layer is largely dependent on the anisotropy of the liquid water diffusivity of the tuff stone.

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