Technical Note

Intensive Measurements of Soil Pore Water Pressure for Analyzing Heterogeneous Hydrological Processes on a Hillslope

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We conducted intensive tensiometer measurements of soil pore water pressure to examine the spatial heterogeneity of hydrological properties at a mountainous hillslope at the Hodaka Sediment Observatory of Kyoto University, Gifu, central Japan. The detailed measurements revealed that pressure head at the soil–bedrock interface was highly variable in terms of waveform, value, and timing throughout the slope. On the basis of its variation, pressure head was classified into four general groups (types 1-4). Type 1 showed rapid peaks with near-zero pressure values coinciding with rainfall peaks and type 2 showed almost no responses to hyetographs. Compared to types 1 and 2, types 3 and 4 showed unique characteristics. That is, type 3 showed delayed peaks in comparison with hyetographs and gradual recession limbs, indicating the existence of groundwater seepage from the bedrock fracture. Moreover, it also represented the characteristic base flow discharge from whole basin area. Type 4 showed sharp pressure spikes coinciding with rainfall peaks, suggesting vertical infiltration within macropores and irregular preferential flows above the bedrock. In this study, we successfully detected various patterns of soil water behavior within the relatively narrow area that characterized the hydrological processes of the hillslope and the watershed.

1. INTRODUCTION

Recent studies have demonstrated that heterogeneous movement of soil water has a large effect on shallow landslide occurrence on steep hillslopes, such as through pipe flow [Jones, 1981; Uchida et al., 2002], macropore flow [Noguchi et al., 1997], tree effects [Liang et al., 2007], and flow through bedrock [Uchida et al., 2003]. Although many studies have clarified these mechanisms, it is still difficult to precisely predict runoff generation and the occurrence of shallow landslides. One reason for this difficulty is that the detailed and accurate process of water movement in natural soil is still poorly understood. In natural hillslopes in mountainous regions, water movement through soil can be highly complex within a relatively narrow area. Most previous studies, however, have examined relatively wide areas without spatially dense pore water pressure measurements [e.g., Montgomery et al., 1997, 2002; Nishiguchi et al., 2005]. In this study, we conducted intensive measurements of pore water pressure to identify heterogeneous soil water movement at a high spatial resolution.

Fig. 1 Topographic maps of the study hillslope and tensiometer observation points
2. METHOD

Observations were performed in a headwater basin of the Hirudani experimental basin in the Hodaka Sediment Observatory of Kyoto University in Gifu, central Japan (36°15’N, 137°35’E). As shown in Figure 1, the study hillslope area is located at a foot of the valley-side slope facing southeast. The study area has a mean gradient of 40° and is underlain by weathered granite porphyry. The regolith ranges in thickness from 22 to 250 cm.

An old landslide scarp is adjacent to the slope.

At the hillslope site, we installed 57 tensiometers attached with Copal Electronics PA-850-102V-NGF pressure transducer in a 12 m \( \times \) 12 m area at intervals of 1–2 m (Fig. 1). At each point, we observed variation in soil pore water pressure (pressure head) at the soil–bedrock interface. The pressure head values were recorded at 150 sec intervals during no-rain periods and 20 sec intervals during rainfall events using Campbell CR1000.
Every tensiometer was installed just above the soil-bedrock interface. In this study, bedrock is defined as the layer with an $N_c$ value exceeding 100, as measured by a cone penetrometer with a 60° bit, a cone diameter of 20 mm, a weight of 2 kg, and a fall distance of 50 cm. The $N_c$ value denotes the number of blows required for 10 cm penetration. Observation was conducted from 28 May to 22 October 2008.

Additionally, we observed discharge from the watershed (area: 0.85 km$^2$) that included the hillslope site. The outlet of the watershed was about 1 km downstream from the hillslope site.

3. RESULTS AND DISCUSSION

3.1 Pressure head variation

First, we focus on the 29 June 2008 rainfall event (total: 112 mm, maximum: 10.2 mm/h), which was the heaviest rainfall event at the study site in 2008. A rainfall event (total: 30 mm) anteceding the 29 June event was occurred on 23 June 2008. Therefore, the 29 June event had a relatively dry initial condition. Figure 2(a) shows the hyetograph and hydrograph for the event. Figure 2(b) shows the pressure heads observed at four points (P1–P4). Figure 3 illustrates the pressure head distribution on the soil–bedrock interface for the snapshot periods denoted as T1–T5 in Figure 2.

Before the rainfall event [T1; 20:00 on 28 June; Fig. 3(a)], the saturated zone ($\psi \geq 0$) was distributed in the lower section and upper right section of the slope. Especially high pressure was observed near P3 despite the dry condition.

Six hours after the beginning of rainfall [T2; 4:00 on 29 June; Fig. 3(b)], the pressure head had not yet responded to the rainfall at P1. However, the pressure head spiked at P4 and some other points [denoted by crosses in Fig. 3(b) and (c)] scattered over the whole slope, forming a quite heterogeneous distribution of the saturated zone. At the peak of rainfall [T3; 9:00 on 29 June; Fig. 3(c)], pressure heads at P1 and P4 reached peak values. P2 showed almost no response, and P3 showed a slight increase. A transient saturated zone extended upward throughout the slope. However, some points in the middle and lower sections remained unsaturated.

Approximately 16 h after the cessation of rainfall [T4; 16:00 on 30 June; Fig. 3(d)], the pressure head peaked at P3, 31 h from the peak of rainfall. As a result, the saturated zone expanded in the upper right section [denoted by circles in Fig. 3(d) and (e)]. Additionally, P4 and some points where the pressure head spiked during the rainfall peak still showed high values.
Approximately 2 days after the cessation of rainfall (T5; 0:00 on 2 July; Fig. 3(e)), the transient saturated zone in the upper section had mostly disappeared, and the distribution of the saturated zone was nearly the same as it had been before the rainfall event, except in the upper right section where the pressure head remained high.

Figure 4 summarizes the long-term variations of the hyetograph, hydrograph [Figure 4(a)], and pressure head values at P1 to P4 [Figure 4(b)]. At P1, the pressure head showed rapid peaks with near-zero pressure values coinciding with rainfall peaks, and had negative values during no-rain periods. At P2, the pressure head exhibited almost no responses to hyetographs throughout the observation period. At P3, the pressure head maintained a high value throughout the observation period, showing delayed peaks corresponding to large rainfall inputs during heavy storm events, followed by gradual recession limbs. At P4, the pressure head spiked sharply and had quite high positive pressure values coinciding with individual rainfall peaks.

3.2 Variation over the whole slope

The pressure head variations over the whole slope were classified into four general groups (types 1–4), each of which exhibited similar trends at each of points P1 through P4, respectively. Figure 5 plots the location of each tensiometer and the type of response observed within the slope, and illustrates the bedrock topography and saturated and unsaturated regions under the no-rainfall condition.

Most type 1 points were distributed at the upper section of the slope. All of the points were unsaturated under the no-rainfall condition and showed nearly the same variation characteristics as at P1 [Fig. 4(b)]. Type 2 points were mainly distributed at the lower section of the slope. They were saturated or nearly saturated throughout the observation period and exhibited no remarkable changes, as at P2.

Compared to types 1 and 2, types 3 and 4 showed unique characteristics in both temporal variation and location. Type 3 was distributed at three points in the upper right section of the slope, corresponding to a hollow in the bedrock. These points showed similar responses to P3, as will be discussed below in comparison with the discharge hydrograph.

The points categorized as type 4 were scattered over the slope. The pressure head at type 4 points responded to rainfall more quickly than that at the type 1 points, as shown in Figure 2(b). Such sharp and rapid responses may result from vertical preferential flow within macropores [Tress et al., 1998]. As a result of these sharp and rapid responses, a high pressure zone (i.e., \( \psi > 50 \) cm) expanded from P4 through P3 at the peak of the rainfall [T3; Fig. 3(c)], implying the existence of preferential flow pathways that flush out water just above the bedrock. At the same time, some of the type 4 points were also found in the middle left section of the slope, where no bedrock hollow existed. This result does not correspond with that of a previous study demonstrating the relationship between preferential pathways and bedrock topography [Freer et al., 2002]. In this study, high-resolution pressure head data revealed the heterogeneous distribution of preferential pathways.

3.3 Discharge hydrograph

The hydrograph for the 29 June 2008 rainfall event [Fig. 2(a)] was characterized by rapid and
delayed peaks. The rapid peak coincided well with the peaks of rainfall and pressure head at P1 and P4 [T3; 9:00 on 29 June 2008; Fig. 2] and was considered to be saturated overland flow and subsurface storm flow through the regolith zone. We could not clarify the contribution of the preferential flows above the bedrock to the discharge hydrograph because we had no data for runoff just below the study hillslope. Nonetheless, the preferential flows above the bedrock probably affected rapid increases in the discharge rate from the slope, because types 1 and 4 caused rapid increases in hydraulic head. As shown in Fig. 5, only one tensiometer showed type 4 response in the lowest part. It indicates that the subsurface water which made rapid peak of discharge was flushed out through the narrow preferential flow pathway.

The delayed peak (21:00 on 2 July 2008; 21 hours after T5) was considered to be relatively slow throughflow, as in a low relief hillslope with thick colluvium [Anderson and Burt, 1978] or as for flow through bedrock fractures [Hirose et al., 1994; Onda et al., 2001]. In the case of the study area, there is a high possibility of bedrock fracture flow because the hillslope site has relatively steep topography and a thin soil layer, as previously described. The net time needed for water to flow through the fracture network inside the bedrock should create the delayed peak.

It is notable that the seasonal waveform of the pressure head at P3 showed high correlation with the discharge hydrograph [Fig. 4(b)]. This result suggests that the pressure head variation at P3 (and at other points where type 3 was observed) reflects the discharge rate of bedrock fracture flow, which has the dominant effect on base flow discharge from the whole watershed.

4. CONCLUSION

Using intensive measurements of pore water pressure, we identified the unique variations of pressure head which characterize the hydrological processes of the study hillslope and the whole watershed. In particular, we detected the groundwater seepage from the bedrock fracture at three points (i.e., type 3 responses). This result was confirmed by the fact that the waveform for these points corresponded well to the base flow discharge hydrograph, and that they were located in the hollow of the bedrock. Furthermore, we detected pressure head spikes at 10 points (i.e., type 4 responses). The variation and location characteristics indicated the existence of vertical preferential infiltrations within macropores and preferential flow pathways above the bedrock, which were distributed irregularly.

We concluded that various patterns of pore water pressure behavior existed within the relatively narrow area, making the hydrological properties of the hillslope spatially and temporally heterogeneous and potentially having a large effect on slope stability. This finding is particularly relevant to ongoing attempts to predict landslides by real-time observation of pore water pressures and for revealing the detailed mechanisms of shallow landslides affected by heterogeneous soil water movement.

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REFERENCES
Hirose T., Onda Y., Matsukura Y. (1994): Runoff and solute characteristics in four small catchments with different bedrocks in the Abukuma mountains, Japan, Transactions, Japanese Geomorphological Union, Vol. 15A, p. 31-48


