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SUDDEN RISE OF GROUNDWATER TABLE CAUSED BY SEVERE RAINFALL

By

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Abstract

Strange type of rainfall effect is found in our continuous observations on a shallow well, that sudden rise of water level always follows the beginning of severe rainfall. Raised level is maintained for some time and then begins to show gradual rise with advancing of infiltrating water. It is noted that the former sudden rise always reached a definit amount, *viz.* about 6 mm. This fact may be explained by propagation of increasing pressure in soil air controlled with escaping process of air bubbles through the subsurface water continuous region.

1. Observed results of rainfall effects

Effects of rainfall on the water table are generally illustrated as gradual rises somewhat later to the beginnings of rainfall. Such delays were often regarded as depending on time taken by infiltration from surface to the water table. Water level in an observed shallow well also shows similar effect in most cases of usual rainfall. It starts to rise 0.5 to 2 hours later to the beginning of rainfall (see Fig. 1). It is noted, however, that a strange type of rainfall

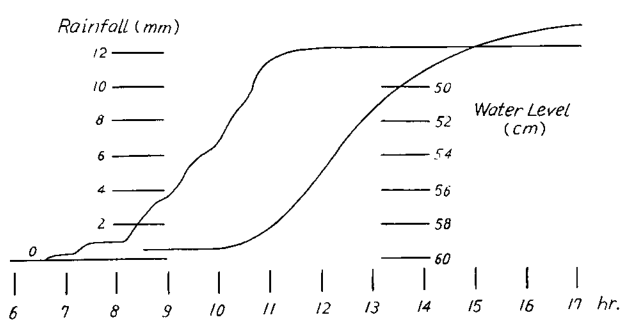

Fig. 1. An example of usual type of rainfall effect on the water level in an observation well. Water level is represented by the depth measured from ground surface and rainfall by the integrated amount from beginning of rain.

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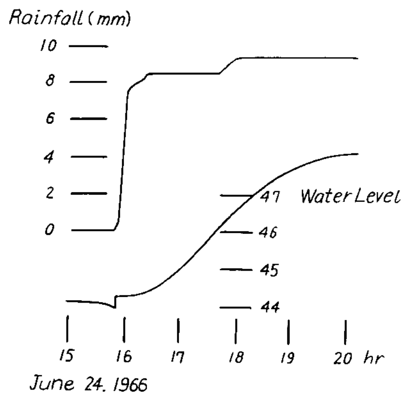

Fig. 2. An example of sudden rise of water level in an observation well. Water level and rainfall are represented in the same manner as in Fig. 1.

effect is always observed at severe rainfall, intensity of which is over 3 mm per ten minutes. Characteristics of such a type are clearly shown as follows and an example is illustrated in Fig. 2.

(1) Water table suddenly rises with the beginning of severe rainfall. The raised height always amounts to about 6 mm, which seems to be independent on other factors such as the rate of precipitation or ground water level.

(2) The raised level remains for some time and then gradual rise begins suggesting the influence of usual type of rainfall effect as previously mentioned. Possible explanation for the rapid response of water table rising may be that it occurs with pressure propagation through soil air rather than with water infiltration to the water table.

Adrian *et al.* [1966], Peck [1965] and Youngs *et al.* [1964] studied the process of infiltration into the bounded soil column with entrapped air being compressed. Peck [1960] discussed the variation in the water table caused by the compression of soil air. Much greater amount of increase in soil air pressure during infiltration were reported in these experimental studies than experienced in our field observations.

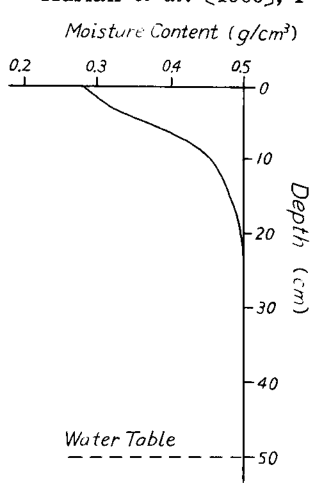

Fig. 3. An example of vertical distribution of moisture content near the observation well. Moisture contents represent the weights of water in unit volume of soil samples at various depths. Water table is indicated by broken line.

An example of soil moisture distribution near the well is indicated in Fig. 3 (Kawanishi [1966]). As the compression of soil air required to produce increase of about 0.6 cm in water column is estimated being only slight, infiltration of rain water would be negligibly small if soil air existing as in Fig. 3 could not escape through the surface. On the contrary from a viewpoint of the later gradual rise of water level, infiltration must be supposed to advance to the water table. It is then concluded that the greater part of soil air escapes to the atmosphere during the process of infiltration. Considering that characteristics involved in the observed sudden rise of water table are quite regular, there would be a general rule governing the escaping process of soil air through infiltrating region though such a process seems to be occured under irregular conditions.

2. Hydrological model of unsaturated region in soil layer

Water table is defined as the surface on which the pressure of soil water is equal to that of the atmosphere, and practically corresponds with water level in the well. Soil water above it is sustained by the capillary force and is in equilibrium with pressure of soil air in static condition. Vertical distribution of moisture content shows gradual decreasing towards the surface from nearly saturated zone extending about 20 cm above the water table (in Fig. 3). The unsaturated zone will be studied modeltically by dividing into two regions as follows.

(*a*) *Air continuous region*—— Soil air is connected each other in the pore space down to some depth under the ground surface. Air is movable without difficulty and soil water isolates in each part of soil pores.

(*b*) *Water continuous region*—— Soil water is connected each other in the pore space within the region near the water table and is movable. Soil air is entrapped in the water as bubbles.

The intermediate region between them is expected, of course, to exist, in which water and air are both connected, but we assume it as involved in the water continuous region in this paper. In Fig. 4, the broken horizontal line connecting B and G represents the boundary separating both regions.

The relation between capillary pressure (p) and soil moisture content (θ)

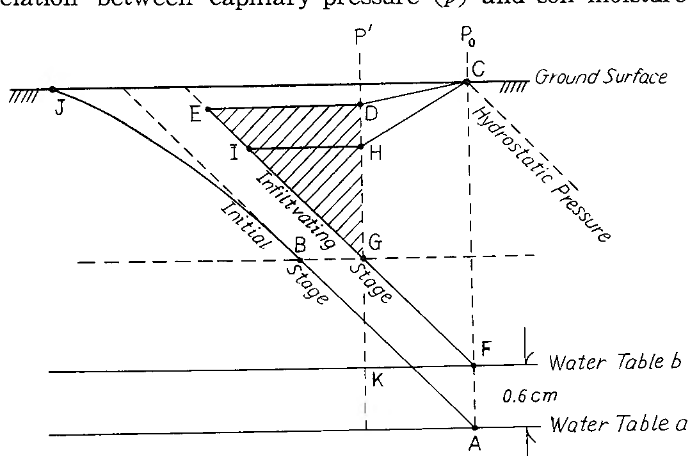

Fig. 4. Profiles of capillary pressure illustrated schematically at each stage of infiltration. Solid line JBA represents initial stage before rainfall and CDEF or CHIF infiltrating stage.

for soil samples in this field is experimentally obtained and is found for the high moisture content being approximately expressed as the next linear formula.

$$p_0 - p = 520(\theta_s - \theta), \qquad (1)$$

where p_0 denotes the atmospheric pressure, p is the water pressure, both expressed in terms of the height of water column (cm), and θ_s is the saturated value of moisture content θ. The vertical distribution of the capillary pressure p is schematically shown in Fig. 4 by the line (JBA) of initial stage. It coincides nearly to that of the equipotential in static state, except near the surface where the moisture content is lowered because of the effect of evapotranspiration (particulary in the root zone).

3. Changes in distribution of capillary pressure with severe rainfall

During the rain of not so large intensity, the pressure of soil air is kept nearly equal to that of atmosphere as they are still connected each other. However at severe rainfall, water perfectly covers the soil surface and cut off the soil air from the atmosphere. Soil air is then compressed independently upon the atmospheric pressure with the advance of infiltration. Observed result on sudden rise of water table means that the air pressure p' in the closed region is always higher than atmospheric pressure p_0 by the constant amount i.e. 0.6 cm. Fig. 4 illustrates the assumed process of variations of capillary pressure with the advance of infiltration applicable to this result. The solid line along JBA indicates the distribution of capillary pressure in unsaturated zone at the initial stage when the water table lies at the level denoted by a. When the ground surface is wetted nearly to saturation at the beginning of sever rainfall, capillary pressure in surface layer is assumed to become nearly p_0 being in equilibrium with saturated moisture content by equ. (1). Soil air in the downward layer from this wetted surface is cut off from the atmosphere and become compressed by infiltrating water. The pressure increase causes rapid rising in water table up to the level b, and the distribution of capillary pressure becomes to be indicated by the solid line CDEF.

Both CD and GF represent the water continuous regions and the air continuous region is remained between them as shown by shaded area. As the wetting front advances from D to H, the air continuous region contracts and soil air becomes entrapped as bubbles by growing water continuous region. The main problem in this paper is to explain the mechanism in which the air pressure in contracting air continuous region is maintained at constant value until the wetting front reaches the level G.

4. Formation of air bubbles

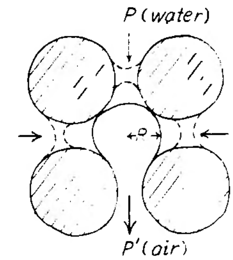

Fig. 5. Advance of wetting front in a soil pore.

In the upper region of unsaturated layer, some quantities of water are sustained by the capillary force among the soil particles as shown by the broken line in Fig. 5. At that time, the capillary pressure (p) is given by the next relation.

$$p_0 - p = 2T/gr,$$

where r is the radius of curvature of the water surface and T is the surface tention of water. The values of r and then p increase during infiltration. With the advance of infiltration, wetting front cut off the lower soil air from the atmosphere and the air pressure changes from p_0 to p'. Ahead of the wetting front, water advances along the walls of soil particles and encloses soil air as a bubble in each pore. The bubble is eventually isolated from the air continuous region. At the instant when bubble is isolated, the pressure p' in the bubble is assumed equal to that in the lower air continuous region. The state of equilibrium between air and water at the wall of each bubble is expressed as

$$p' - p = 2T/gR, \tag{2}$$

where R means the radius of the largest spherical bubble. In order to keep p' constant as deduced from observed results, the value of $p+2T/gR$ must be constant throughout infiltration. Although the value of R is determined by the geometry of soil particles if size and packing of grains are uniform, such a condition cannot be expected in the actual soil layer. But even if not uniform at given level as indicated in Fig. 6, it is possibly expected from equ. (2) that pores having smaller values of R are filled with infiltrating water earlier than the larger pores. Thus air is remained as bubble only in the largest pore at each level. Then, R in equ. (2) is expected to keep nearly constant in spite of irregularities of soil packings along the course of advancing front. It may be therefore reasonable supposition that simple form of equ. (2) is applicable at any level of wetting front during infiltration.

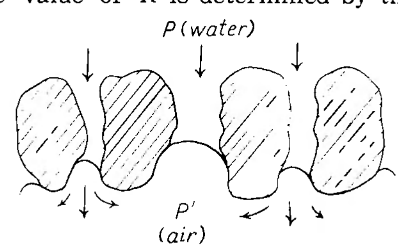

Fig. 6. Advance of wetting front into irregular soil.

On the other hand, the value of R is supposed to be not changed before and during infiltration at the upper boundary of the lower water continuous region shown as level BG in Fig. 4. Then, observed result keeping the rise of water table as 0.6 cm suggests that air pressure p' during infiltration is always 0.6 cm higher than before rain fall.

Substituting that $p'=p_0+0.6$, $T=70$ (dyne/cm) and $g=980$ (cm/sec^2) into equ. (2),

$$p_0-p+0.6=2T/gR=1/7R. \tag{3}$$

From this equation, capillary pressure at the wetting front is found to be kept at constant value p throughout infiltration, as shown in Fig. 4. The left-hand side implies the height of water continuous region above water table, i.e. GK in Fig. 4, which is assumed to amount to about 20~30 cm, considering the vertical distribution of soil moisture. The estimated value of R from equ. (3) amounts to 0.007~0.005 cm, which is not so inconsistant with the actual pore size distribution.

It seems insufficient only by the above-mentioned discussion to explain perfectly the characteristics involved in the infiltration process of severe rainfall. But it is interesting to suggest the possibility that the escaping process of air as bubbles through the wetting front plays the important role in infiltration mechanism. The more detailed investigations are required on the relation between capillary pressure and the behavior of entrapped soil air to make clear the motion of water through unsaturated zone.

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