Postprint: Simulation of Water Transport Patterns in Loess at Heifangtai, Gansu

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Abstract

Based on field experiments and applying the theory of saturated-unsaturated soil water movement, Hydrus software was utilized to conduct numerical simulation of water transport patterns in the vadose zone at Heifangtai, Gansu Province, analyzing variation patterns of water content at different soil profile depths, comparing simulated results with measured data, and applying fitted parameters to two different media. The results show that: (1) soil water content exhibits peak-valley fluctuation patterns; (2) in both homogeneous loess layers and loess layers overlain with 5 cm thick silty loam, soil water infiltration rate and phreatic evaporation rate both decrease with increasing phreatic water depth, with the soil water infiltration rates of the two media converging to the same value at phreatic depths below 300 cm, while the phreatic evaporation rate of silty loam-containing profiles is lower than that of homogeneous loess. These findings indicate that water content variation exhibits spatiotemporal characteristics, and that soil water infiltration rate and phreatic evaporation rate vary with phreatic depth following generally similar patterns, which is of significant importance for studying water distribution in landslides.

Full Text

Abstract

This study numerically simulates vadose zone water migration mechanisms by analyzing saturated-unsaturated soil hydraulic parameters using Hydrus-1D software, based on outdoor tests and saturated-unsaturated soil moisture migration theory. The model was verified through field experiments, and the fitted parameters were applied to two soil types: homogeneous loess soil and a 5 cm thick silty loam overlying layer. Results demonstrate that: (1) soil moisture content exhibits fluctuating peak-valley patterns; (2) both soil water infiltration rate and phreatic water evaporation rate decrease with increasing phreatic water level in the two soils. When the phreatic water level is less

than 300 cm, the infiltration rates of both soil types converge to similar values, while the evaporation rate of the silty loam medium is lower than that of the homogeneous loess. In conclusion, water content changes exhibit distinct spatial and temporal characteristics, and the infiltration and phreatic evaporation rates of both soils show similar responses to phreatic water level variations. These findings provide a scientific basis for understanding water distribution and changes in landslide bodies.

1.1 Study Area

The research site is located at Heifangtai in Gansu Province, covering an area of 13.5 km^2 with an elevation of 120 m. Annual precipitation ranges from 187.6 to 317 mm, with over 70% occurring during the rainy season (July-September). The local groundwater depth is approximately 80 m. Previous studies indicate that more than 80% of landslides in this region are triggered by water infiltration processes [**?**, **?**]. The Hydrus-1D software was employed to simulate soil water migration, with model validation conducted through field monitoring of soil moisture dynamics.

1.2.2 Soil Hydraulic Parameters

Soil hydraulic parameters were determined using the van Genuchten model:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|h|)^n]^m}$$

where θ is the volumetric water content (cm^3 · cm ^{3}), h is the pressure head (cm), θ_s and θ_r represent saturated and residual water contents respectively (cm^3 · cm ^{3}), α and n are empirical shape parameters, and $m = 1 - 1/n$ with $0 < m < 1$.

The hydraulic conductivity function is given by:

$$K(\theta) = K_s \theta^l \left[1 - (1 - \theta^{1/m})^m\right]^2$$

where $K(\theta)$ is the hydraulic conductivity (cm/d), K_s is the saturated hydraulic conductivity (cm/d), and l is the pore connectivity parameter.

Parameter fitting was performed using the Levenberg-Marquardt algorithm implemented in Hydrus-1D, with the objective function minimizing the sum of squared differences between observed and simulated values. The fitting process utilized 10,000 cm as the maximum pressure head range.

1.2.4 Model Setup and Boundary Conditions

The simulation domain was discretized into a one-dimensional vertical column with nodal spacing of 1 cm near the surface, gradually increasing to 5 cm at depth. The upper boundary condition was set as an atmospheric boundary with surface runoff, while the lower boundary was assigned a variable pressure head condition based on measured groundwater levels. Initial conditions were established from field-measured soil moisture profiles. The simulation period covered seasonal freeze-thaw cycles with a daily time step.

3.4 Soil Water Infiltration Rate

Infiltration rates varied significantly with depth and soil layering. For the homogeneous loess profile, the infiltration rate was 1.618 cm · d ^{1} at 80 cm depth. In the layered profile with 5 cm silty loam at the surface, infiltration rates ranged from 1.660 to 1.748 cm · d ^{1} in the 10-40 cm zone, decreasing to 1.618 cm · d^{1} below 300 cm. The presence of the silty loam layer increased near-surface infiltration capacity by approximately 3-8% compared to the homogeneous profile.

3.5 Phreatic Water Evaporation

Phreatic water evaporation rates exhibited similar depth-dependent patterns. At 80 cm depth, the evaporation rate was 1.68 cm · d ^{1}, decreasing to 1.641-1.716 cm · d ^{1} in the 10-40 cm zone, and further reducing to 1.645 cm · d ^{1} in the 40-150 cm zone. Below 300 cm, the rate stabilized at 1.110 cm · d ^{1}. The silty loam layer reduced evaporation losses by 15-20% compared to the homogeneous loess profile, particularly in the shallow subsurface zone.

Results and Discussion

Field monitoring data from July 10 and October 8, 2013, were used to validate the model predictions [Figure 5: see original paper]. The simulated soil moisture profiles showed good agreement with measured values across different depths, with standard deviations less than 0.02 cm^{3} · cm ^{3} . The fitted hydraulic parameters are summarized in , with α values ranging from 0.001 to 0.005 cm ^{1} and n values between 1.2 and 1.5 for the loess materials.

The temporal evolution of soil moisture during the melting period [Figure 3: see original paper] and freeze-free period [Figure 4: see original paper] demonstrates distinct seasonal patterns. Moisture content fluctuations correlate with precipitation events and temperature variations, showing peak-valley dynamics that are more pronounced in the upper 50 cm of the profile. Phreatic water evaporation rates [Figure 8: see original paper] decrease exponentially with increasing groundwater depth, following the relationship described by (**??**).

The simulation results indicate that when the phreatic water level exceeds 300 cm, the influence of capillary rise on surface evaporation becomes negligible. This threshold is critical for assessing landslide stability, as reduced soil moisture at depth decreases pore water pressure and enhances slope stability. The presence of a thin silty loam layer modifies the hydraulic response by increasing water retention in the shallow subsurface while reducing deep percolation losses.

Conclusion

This study successfully applied Hydrus-1D to simulate water migration in loess soils under variable boundary conditions. The validated model provides reliable predictions of infiltration and evaporation rates for both homogeneous and layered soil profiles. The findings offer a scientific basis for understanding water distribution mechanisms in landslide-prone areas and can support early warning systems for rainfall-induced landslides in loess regions.

References

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