Study on the Influence of Pore Water Pressure on the Stability of Slope

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Abstract. The influence of pore water pressure on slope stability under water drop and seismic action is studied in this paper, taking an embankment as the research object. The temporal changes of seepage field are analyzed first, and then the stability of dam slope is investigated by coupling the stress field with the seepage field. During the process of water drop, the minimum safety factor of slope stability appears at the moment when it stops falling. The greater the falling speed is, the faster the pore water pressure dissipates, and the smaller the safety factor is. Seismic action stimulates the increase of excess pore pressure, and whether to consider the coupling effect of seismic load and pore pressure change will make the results of stability analysis quite different. The cumulative effect of pore pressure may be the crucial factor of the dynamic instability of two-phase media slopes.

1. Introduction

A large number of engineering cases show that the pore water pressure (PWP) is an essential factor to cause landslides. It is found that the seepage is often the key to the slope stability\cite{1,2}. Rainfall and earthquake are sensitive factors affecting the slope stability\cite{3}. It is proposed that the influence of earthquake and groundwater on slope stability would be underestimated by simply superposing them, which is consistent with the results of laboratory shaking table tests\cite{4}. It is also found that the existence of dynamic pore water pressure would accelerate the failure of slope under high dynamic stress through numerical simulations and laboratory tests\cite{5}. All these studies show that the pore water pressure is an important factor in the stability analysis of two-phase medium slopes, the changing process and influence of which should be carefully considered.

In this paper, the unsteady seepage field and the dynamic response of an embankment are investigated by coupling the seepage field and the seismic field. The change of excess pore water pressure excited by unsteady seepage and seismic load are mainly considered, as well as its influence on the stability of slope.

2. Computation model and parameters

2.1. Computational model and boundary conditions

An embankment with a height of 44m is studied in this paper. The upstream water level is 33 m, while the downstream water level is flush with the top of the dam foundation. Figure 1-2 show the geometric dimensions, positions of characteristic points and the finite element mesh diagram.
The boundary conditions are as follows: 1) \(ab, bc\) are the infiltration boundaries. 2) \(nf\) is the outflow boundary. 3) the surrounding bedrock is treated as a fixed boundary.

### 2.2. Soil parameters

In this example, the dam shell is made of clay sand, while the dam body is medium sand and the foundation is granite. The parameters of the soil layers are shown in Table 1. In unsaturated seepage analysis, Fredlund-Xing model is used to estimate the variation of permeability coefficient with matrix suction. In the dynamic analysis, the equivalent linear model is used.

| Soil layer | \(\gamma\) (kN/m\(^3\)) | \(c\) (kPa) | \(\varphi\) (\(^\circ\)) | \(k_s\) (m/s) | \(\nu\) |
|------------|-----------------|---------|--------|----------|------|
| ① sludge sand | 18 | 5 | 34 | \(10^{-5}\) | 0.40 |
| ② medium sand | 18 | 0 | 34 | \(10^{-5}\) | 0.40 |
| ③ granite | 20 | \(3 \times 10^4\) | 50 | \(10^{-12}\) | 0.25 |

### 3. Results and discussion

Figure 3 shows the distribution of pore water pressure under steady seepage. The stability analysis of the upper and lower reaches of the dam are shown in Figure 4. At this time, the upstream and downstream slopes are in a stable state, and there is no danger of landslide.

In order to study the influence of pore water pressure under unsteady seepage field, the correlation analysis is made by taking the reservoir water drop as an example. The water level on the right side of the dam is always flush with the top of the dam foundation, and that of the left side falls at a speed of 3 m/d, 11 m/d and 33 m/d, respectively from a distance of 33 m.

Figure 5 shows the change of the infiltration line at different water drop speeds. It can be found that the drop speed has an obvious effect on the change of the free surface. At any time during the falling period, the greater the water level deceleration speed is, the more inclined the infiltration line near the upper surface will be. The change of infiltration line reflects the process of consolidation and drainage, which means the slope tends to be stable gradually.
The changes of slope stability safety factor is shown in Figure 6. Taking the upstream slope as an example, the safety factor decreases first and then increases with time. When the water level falls completely, the slope stability safety factor just reaches the minimum value. And the larger the water level deceleration speed is, the smaller the minimum safety factor in the whole process of the analysis period is. After falling, the safety factor increases gradually with time, which increases rapidly at the early stage and slows down later. This is because the slope enters the consolidation drainage process when the upstream water disappears, and it will be closer to the steady state with time. For the downstream slope, the stability safety factor increases with the decreasing water level, and it also keeps increasing after falling. This is because the drop in the water level will increase the matrix suction in the downstream side of the slider, which is beneficial to the stability of the body.

Considering the dynamic action, the slope failure is mainly affected by the horizontal vibration. So only the horizontal seismic wave is input into the calculation, as shown in Figure 7.
Figure 7. Time history curve of seismic wave

Figure 8 reflects the development of pore water pressure at each characteristic point, and it can be found that: 1) from the growth process of pore pressure during the period of vibration, the points in the dam of the same height meet the requirements of the excess pore pressure that the riverward surface > the landward surface > the dam inside. 2) from the numerical changes of the pore water pressure before and during the earthquake, the riverward surface > the dam inside > the landward surface. But the increment of the landward surface is limited. So the final pore pressure relationship remains that the riverward surface > the dam inside > the landward surface.

Figure 8. Development of pore water pressure at characteristic points under earthquake

Based on the coupling effect of seismic load and pore water pressure, not only the influence of pore water pressure but also the excess pore pressure excited by dynamic load is considered in the above analysis. From figure 9-11, we can find: 1) when considering pore water pressure without the coupling
effect of seismic load and pore pressure, shallow sliding is easy to occur, and the sliding surface is relatively flat. Considering the coupling effect, the position of the sliding surface is much deeper, which is prone to deep sliding. 2) when the pore water pressure is not considered at all, the safety factor is larger and the anti-seismic capacity of the dam is overestimated. When the pore water pressure and its coupling effect with earthquake load are both considered, the safety factor is relatively small, which indicates that the coupling effect cannot be ignored.

Figure 9. Slope stability analysis in consideration of the coupling effect (t=14 s)

Figure10. Dynamic stability analysis by pseudo-static method

Figure 11. Slope stability analysis without consideration of pore water pressure (t=14 s)

Figure 12. Time history curves of slope safety factor during earthquake

From figure 12, it can be seen that: 1) the safety factor is always large without considering pore water pressure, but it decreases greatly after considering that (no matter whether the coupling effect is considered or not), which indicates that the pore pressure is an important factor affecting the stability. 2) the stability safety factor shows that the coupling effect of seismic load and pore pressure reflects the accumulation of pore pressure under dynamic action, and this cumulative effect is often the
decisive factor affecting slope instability. 3) the evaluation results of slope stability can be obtained according to the judgment of slope instability by Liu[6], as shown in Table 2. When considering the pore water pressure without coupling effect, it exaggerates the effect of water at the initial stage of the earthquake, but underestimates it in the end.

| Slope  | Not considering PWP | Considering PWP without coupling effect | Considering PWP with coupling effect |
|--------|---------------------|----------------------------------------|-------------------------------------|
| upstream | safe               | unsafe                                | unsafe                              |
| downstream | safe               | safe                                  | unsafe                              |

As shown above, the slope instability is a process of qualitative change caused by quantitative change. When the pore pressure accumulates to a certain extent, it will play an important role in the slope instability.

4. Conclusions
In this paper, the influence of pore water pressure on the stability of slope is studied. The water drop can cause unsaturated and unstable seepage. The greater the falling speed is, the smaller the safety factor is. The seismic load can stimulate the growth of excess pore water pressure. The coupling effect of seismic load and pore pressure change actually reflects the accumulation of pore water pressure under dynamic action, and this cumulative effect is often the decisive factor affecting the slope instability.

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References
[1] Lu, N., Godt, J. (2008) Infinite slope stability under steady unsaturated seepage conditions. J. Water Resources Research, 44(11):2276-2283.
[2] Srivastava, A., Babu, G.L.S., Haldar, S. (2010). Influence of spatial variability of permeability property on steady state seepage flow and slope stability analysis. J. Engineering Geology, 110(3-4), 93-101.
[3] Kubota, T., Aditian, A. (2014) The Influence of Increasing Rain and Earthquake Activities on Landslide Slope Stability in Forest Areas. In: Agu Fall Meeting. San Francisco. pp. 891-906.
[4] Song, B., Huang, S., Cai, D., et al. (2013) Stability of sandy soil slope under the coupling of earthquake and groundwater. J. Chinese Journal of Geotechnical Engineering, 35(Supplement 2): 862-868.
[5] Huang, S., Lv, Y. (2015) Influence of dynamic pore water pressure on dynamic response of sandy slope under strong earthquake. J. Port & Waterway Engineering, 10;158-167.
[6] Liu, H., Fei, K., Gao, Y. (2003) Time history analysis method of slope seismic stability. J. Rock and Soil Mechanics, 24(4): 553-556.