

## **Study on Mechanism of Concentrated Leakage Accesses Formed Due to Current Scouring in Weak Structure Plane**

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**Abstract.** Weak structure plane is high in plasticity and low in strength, which provides the necessary condition for deforming rock mass and forming concentrated leakage accesses and seepage failure under the effect of groundwater in the long term. Seepage stability of weak structure plane has always been an important engineering geological and hydrogeological problem of water conservancy and hydropower project. At present, their understanding of the mechanism of seepage failure still exist many unsolved problems. Since they rarely studied the concentrated leakage accesses formed due to the weak structure of bedrock before, this article will discuss seepage and deformation problems in weak structure plane. It mainly discusses the current scouring development mechanism of weak structure plane and critical flow velocity and corresponding fissure width when soil particles start at different positions. Finally, it introduces living examples like concentrated leakage accesses formed due to weak structure plane, which means weak structure planes of bedrock can form concentrated leakage accesses under appropriate geological conditions.

### **Introduction**

Weak structure plane often refers to the rock stratum in rock mass with significantly weaker rock property than surrounding rock and obviously smaller thickness of single layer. Since such plane is high in plasticity and low in strength, it has become the primary part where rock mass will deform, concentrated leakage access and seepage failure will form under the effect of groundwater in the long term. Seepage stability of weak structure plane has always been an important engineering geological and hydrogeological problem of water conservancy and hydropower project. Predecessors have done a special indoor and in-situ test study in this aspect. However, they rarely studied seepage and deformation problems of the weak structure plane and there are many unsolved problems still exist in their understanding for the mechanism of seepage failure.

With reference to the classification of seepage and deformation of loose bed, in this article, seepage and deformation of weak structure plane are divided into flowing soil, current scouring and piping. Only mechanism of concentrated leakage accesses formed due to current scouring in weak structure plane is discussed in this article.

### **Mechanism of Concentrated Leakage Accesses Formed Due to Current Scouring in Weak Structure Plane**

#### **General Characteristics of Current Scouring in Weak Structure Plane**

Scouring refers to the phenomenon that soil particles are automatically washed away under the influence of water seepage. Preconditions for happening hydraulic scouring: the first is that there is

space for particle activity; the second is that seepage force (hydraulic power) is strong enough to overcome the cohesive force between particles.

For primary structural plane, although soil mass in it exist fissure and water is flowing, particles directly contacting with underground water in the long term may happen some change that a layer of protective film with closure effect will be formed on the surface to keep the property of soil mass in it. Therefore, permeability of the weak structure plane below the underground water level and through relatively constant hydraulic gradient is far less than the part in the underground water level alternate area or where hydraulic gradient often changes. For weak structure plane in dike foundation, hydraulic gradient changes greatly since outside river water fluctuates frequently. When water level of outside river changes rapidly, water direction may be just the opposite: when outside river floods, flow direction of underground water in weak structure plane is from outside river to dike; when water level of outside river lowers, flow direction of underground water is from dike to outside river. In the long term, mudded intercalation scoured by underground water back and forth is more and more significant, which thus its permeability is greatly improved, and then it develops into the concentrated leakage access <sup>[1]</sup>.

### Critical Flow Velocity of Soil Mass Particles Started and Scoured by Water Flow

Hereinafter mechanism of concentrated leakage accesses formed due to hydraulic scouring in weak structure plane will be studied from the angle of mechanics <sup>[2]</sup>. When analyzing hydraulic scouring of soil mass particles in mudded intercalation, it is necessary to consider the relatively high or low position of particles on the surface of soil mass because it directly decides whether the particles can be washed away in other same conditions. This relative position is expressed as exposure degree  $\Delta$  (refer with Figure 1). The smaller the exposure degree  $\Delta$  is, the more fully soil particles expose, which means it is more easily washed away. To eliminate the influence of particle diameter, relative exposure degree  $\Delta'$  is often used to express, that is

$$\Delta' = \Delta / R \tag{1}$$

where,  $\Delta'$ - relative exposure degree,  $\Delta$ - exposure degree,  $R$ -radius of the soil particle.

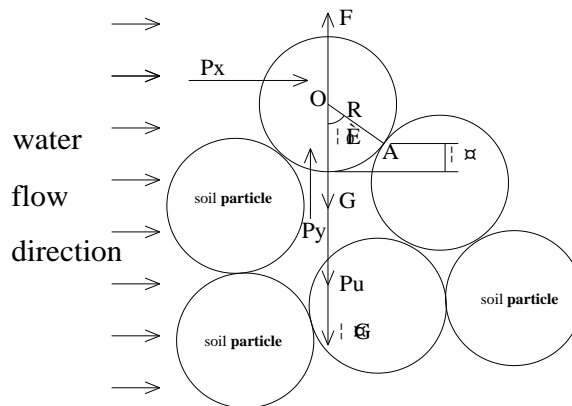


Figure 1. Stress analysis of soil particles in mudded intercalation.

Assume that the structure of soil mass particles of mudded intercalation in weak structure plane is as show in Figure 1. Inspect stress of soil particles on the surface now. Stresses which act on it are as follows:

**(1) Gravity G is in Vertically Downward Direction.**

$$G = 4\pi R^3 \rho_s g / 3 \tag{2}$$

**(2) Flotage F is in Vertically upward Direction.**

$$F = 4\pi R^3 \rho_w g / 3 \tag{3}$$

**(3) Current Positive Thrust Px is in Level Towards the Right According to the Direction Described by Figure.**

$$P_x = C_x \pi R^2 \rho_w V_{b,c}^2 / 2 \quad (4)$$

Current positive thrust Px can also be expressed as

$$P_x = \tau_b p R^2 = \rho_w u_*^2 p R^2 = p R^2 \rho_w g H J \quad (5)$$

**(4) Uplift Force Py is in Vertically upward Direction.**

$$P_y = C_y \pi R^2 \rho_w V_{b,c}^2 / 2 \quad (6)$$

Uplift force is caused by dissymmetry of detour flow at the bottom of particles.

Above where,  $\rho_s$  - density of soil particles,  $R$  - radius of soil particles,  $g$  - acceleration of gravity,  $\rho_w \cdot \rho_s$  - density of water body and particles respectively,  $C_x$ 、 $C_y$  - coefficient of positive thrust and uplift force respectively,  $\tau_b$  - shear stress of water flow at the bottom of particles,  $p$  - coefficient,  $u_*$  - friction velocity,  $H$ - depth of water,  $J$ - hydraulic gradient,  $V_{b,c}$ - water velocity at the bottom when particles are actually started.

**(5)  $P_\mu$ , Direction of Adhesive Force Points to the Interior of Soil Mass and State Direction Shown in Figure 3 is Vertically Downward [2].**

$$P_\mu = \frac{\sqrt{3}}{2} \left( 3 - \frac{t}{\delta_1} \right) P'_\mu = \frac{\sqrt{3}}{2} \pi \delta_0^3 R \left( 3 - \frac{t}{\delta_1} \right) \left( \frac{1}{t^2} - \frac{1}{\delta_1^2} \right), t \leq \delta_1 \quad (7)$$

$t$  - half of the distance between soil particles,  $\delta_1$ - the thickness of all bound water,  $K$  - adhesion coefficient,  $2h$  - Distance between two corresponding points (A, A'),  $\delta_0$ - the thickness of a water molecule,  $q_0$  - adhesive force per unit area when  $h = \delta_0$ ,  $\sigma$  - projection of water contact area of films between particles.

**(6) Water Additional Downforce of Film  $\Delta G$**

When particles interact with the multiple particles below, additional downforce  $\Delta G$  can be expressed as

$$\Delta G = \sqrt{3} \pi K_1 \rho_w g H R (\delta_1 - t) (3 - t / \delta_1) \quad (8)$$

Prior 6 forces above take the moment of point A according to the figure, formula is

$$P_x (a + R \cos \theta_0) + P_y (b + R \sin \theta_0) + F R \sin \theta_0 = (G + \Delta G + P_\mu) R \sin \theta_0 \quad (9)$$

where, a and b are force arms of  $P_x$  and  $P_y$  respectively. Suppose  $a=b=R/3$  and substitute specific expressions of all forces above into formula (9), achieve the instantaneous incipient velocity of particles on the surface of soil mass  $V_{b,c}$ .

$$V_{b,c} = \varphi(\Delta') \omega_1 (D, H, t / \delta_1) \quad (10)$$

where, D- particle diameter,

$$\varphi(\Delta') = \sqrt[4]{2\Delta' - \Delta'^2} / \sqrt{\left(\frac{4}{3} - \Delta'\right) + \frac{1}{4} \left(\frac{1}{3} + \sqrt{2\Delta' - \Delta'^2}\right)} \quad (11)$$

$$\omega_1 \left( D, H, \frac{t}{\delta_1} \right) = \sqrt{\frac{8gR}{3C_x} \cdot \left( \frac{\rho_s}{\rho_w} - 1 \right) + \frac{\sqrt{3}}{C_x R} \left( 3 - \frac{t}{\delta_1} \right) (\delta_1 - t)} \cdot \sqrt{\frac{q_0 \delta_0^3}{\rho_w t^2 \delta_1^2} \cdot (t + \delta_1) + 2K_1 g H} \quad (12)$$

Based on a lot of actual data, some of the data can be identified: substitute  $q_0 = 1.3 \times 10^9 \text{ kg/m}^2$ ,  $K_1 = 2.258 \times 10^{-3}$ ,  $\delta_0 = 3 \times 10^{-10} \text{ m}$ ,  $\delta_1 = 4 \times 10^{-7} \text{ m}$ ,  $C_x = 0.4$ ,  $g = 9.81 \text{ m/s}^2$ ,  $t = 1.5 \times 10^{-7} \text{ m}$  into formula (12), achieve

$$\omega_1 = \sqrt{107.8R + 1.49 \times 10^{-7} (1 + 0.85H) / R} \quad (13)$$

If adhesion and film water additional downforce don't exist for coarse particles, then

$$\omega_1(D, H, t / \delta_1) = \omega_0(D) = \sqrt{8gR(\rho_s / \rho_w - 1) / (3C_x)} \quad (14)$$

According to the previous steps, if convert water velocity  $V_b$  to seepage velocity  $V_b'$  at the same time, suppose porosity of soil mass in weak structure plane as  $n$ , critical flow velocity  $V_{b,c}'$  can be got.

$$V_{b,c}' = nV_{b,c} = n\varphi(\Delta')\omega_1'(D, H, t / \delta_1) \quad (15)$$

Thus,

$$\omega_1'(D, H, \frac{t}{\delta_1}) = \sqrt{\frac{\sqrt{3}}{C_x R} \left(3 - \frac{t}{\delta_1}\right) (\delta_1 - t) \left[ \frac{q_0 \delta_0^3}{\rho_w t^2 \delta_1^2} \cdot (t + \delta_1) + 2K_1 g H \right] - \frac{8gR}{3C_x} \cdot \left(\frac{\rho_s}{\rho_w} - 1\right)} \quad (16)$$

### Corresponding Fissure Width of Soil Mass Particles Started by Current Scouring

Since instantaneous bottom velocity  $V_b$  of water in weak structure plane is hard to get, it is usually expressed in mean velocity  $V$  along the vertical direction. As thus, it can be related with corresponding fissure width  $b$ . This kind of relationship is seeked as below<sup>[2]</sup>.

At the top of particles on the surface of soil, its water flow bottom velocity is  $V_b = 5.6u_*$ . If action point of water flow on particles is considered, it is relatively appropriate  $2/3D$  distance from bed surface and it is appropriate to take flow velocity at this position as the representative flow velocity when starting. That is

$$V_b = \frac{2}{3} \times 5.6u_* = 3.73u_* = 3.73\sqrt{gJH} \quad (17)$$

According to a large number of measured data, uniform velocity of vertical line  $V$  has such relation with  $u_*$ :

$$\frac{V}{u_*} = \frac{V}{\sqrt{gDJ}} = 6.5 \left(\frac{H}{D}\right)^{0.5 + \frac{1}{4 + 1g\frac{H}{D}}} = \psi \left(\frac{H}{D}\right) \quad (18)$$

$$V_b = 3.73u_* = 3.73V / \psi(H / D) \quad (19)$$

Thus critical incipient velocity  $V_c$  expressed by uniform velocity of vertical line  $V$  can be got:

$$V_c = 0.268\omega_1\psi(H / D)(V / \omega_1) \quad (20)$$

Based on a lot of field survey data,

$$V = 0.55\omega_1 \quad (21)$$

Thus

$$V_c = 0.147\omega_1\psi \quad (22)$$

Suppose there is an equivalent hydraulic fissure which is  $b$  wide in weak structure plane and its unit discharge is

$$q = gb^3 J_f / (12\nu) \quad (23)$$

where,  $\nu$ - kinematic viscosity of water,  $J_f$ - hydraulic gradient along the direction of weak structure plane.

If influence of viscous sublayer on the surface of soil body of mudded intercalation is not considered, velocity of groundwater flow in fissure is

$$V = q / b = gb^2 J_f / (12\nu) \quad (24)$$

Thus, corresponding fissure width  $b$  can be calculated according to mean velocity of critical vertical line  $V_c$ .

$$b = \sqrt{12\nu V_c / gJ_f} = \sqrt{12\nu 0.147 \omega_1 \psi / (gJ_f)} \quad (25)$$

In this way, corresponding equivalent hydraulic fissure width which results in loss of particles on the surface of soil mass in weak structure plane scoured by water has been derived. It means for characteristics of soil mass in a certain mudded intercalation, the smaller hydraulic gradient undertaken by fissure width, the greater the cohesive force of soil mass is and the greater the relative exposure degree of particles on the surface of soil mass is, which make the corresponding fissure width of particles on the surface washed away due to hydraulic scouring become greater. As to the weak structure plane formed due to pressure-torsion fault, the scale of formed tiny fissure is usually larger than structure surface formed in tenso-shear fault and tension joint dense zone. Therefore, the latter easily develops into large-scale fracture to form groundwater enrichment zone. Underground water has good connectivity with the outside so that water-transmitting fault can be formed. If it is developed in the dikebase, under the long-term effect of high water head, concentrated leakage access can be formed very easily, which will affect the safety of dike. From above, on the other hand it also means that influence factors of concentrated leakage accesses in weak structure plane formed under the long-term effect of underground water are underground hydraulic gradient where the weak structure plane is in, cohesive force of soil mass in mudded intercalation which is strength, relative exposure degree of particles on the surface of soil mass, types of structure surface, scale and shape, etc.

## **Living Examples of Concentrated Leakage Formed Due to Weak Structure Planes**

### **Concentrated Leakage Access Formed in Red Bed**

A certain dam's foundation is made of siltstone in the cretaceous period, cemented by carbonate with soft lithologic character and developed fault fissure. Siltstone is mainly composed of fine sand and silt and secondly by clay particles. Reservoir water near pyrite zone 900m from the upstream of dam is acid or strong acid so that it will corrode concrete due to its acid, carbonic acid and very weak crystallinity. When acid water permeates, it will cause erosion damage in red rock of dam foundation. The dam loses normal water retaining ability after put into operation because dam foundation seepage is serious, red rock of foundation is seriously softened and mudded.

### **Concentrated Leakage Accesses Formed in Shell Clastic Rock**

Another example, a certain barrage's stratum is mainly composed of loose deposits in tertiary and quaternary, among which, there are basalts erupted in multiple phases. Since multiphase eruption, structure of tertiary and basalt layers is more complex in profile, which forms multiple weak structure planes. Dam foundation rock (soil) mass is mainly composed of shell clastic rock and low liquid limit clay. Dam body is above shell clastic rock which has not been conducted effective anti-seepage treatment when being built, therefore, parts near hydraulic structure foundation and foundation contact zone in hub and parts inside shell clastic rock are corroded and scoured to leakage accesses of different levels under the long-term water erosion of high water pressure, which results in many dangerous situations and seriously endangers the safety of dam.

It is thus clear that under the long-term effect of groundwater, if it is appropriate, weak structure plane of bedrock can form concentrated leakage access which has a great threat on the hydraulic structure so that it must cause enough attention.

### **Summary**

This article has conducted a tentative classification for seepage and deformation of weak structure plane in terms of standards for seepage and deformation of loose bed after associating the weak structure plane with the concentrated leakage access formed by dam bedrock. Mechanism of concentrated leakage accesses formed due to scouring of underground water in weak structure plane has been discussed. On the basis of predecessors' experience, this article further discusses the critical flow velocity formula of soil mass particles started due to water scouring in different positions, corresponding fissure width for forming the concentrated leakage accesses and influence factors for forming the concentrated leakage access.

### **Acknowledgments**

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### **References**

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