水位急降下에 따른 堤體의 斜面安定解析

Embankment Stability under Rapid Drawdown

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要 旨

水位變化에 따른 相異한 自由水面으로 因하여 堤體內部에 應力狀態가 달라지므로 堤體의 安定解析이 必要하다. 水位가 急降下할 경우 上流側 斜面에서의 自由水面方向이 基礎쪽으로 바뀌어질 때, 上流側 Fill의 安全率을 찾아 보았다. 여기서 下降하는 自由水面과 破壞形態를 찾았으며, 또 安全率을 求하였고, 이로 降下速度 및 動水傾斜를 比較하였다. 實驗에 의한 結果는 다음과 같다.

1. 自由水面의 降下로 因하여 上流側 Fill에 浸透流에 의한 滑動破壞가 일어나고, 破壞高는 各 各의 模型에 따라, 5～10, 9～15, 13～21(cm)이다.

2. 浸透流에 의한 間隙水壓의 影響을 考慮하여 安全率을 구하였으며, 이때 降下速度와 安全率과의 關係에서 堤體의 安全上 降下速度는 0.21～0.28(cm/sec)이어야 하고, 動水傾斜와 安全率과의 比較에서 動水傾斜는 各 模型에서 0.36～0.43 값보다 적어야 함을 實驗上 알았다.

Abstract

Stability analysis of the embankment as to water level varation is the most important problem in the safety of the slope because the stress of embankment inside varies as to drawdown of seepage line. Especially when the water level is rapidly drawdown, because the flow direction of the free surface changes the toe of embankment, the factor of safety comes to small, therefore the embankment is dangered. For the purpose of studing these phenomena, the experimental models are built with sand in the laboratory. In the experimental consideration, the falling seepage line and the shape of failure are measured. This paper intends to study the failure slip surface, the relationship between the factor of safety and drawdown velocity, and hydraulic gradient.

The results of the experimental study are summarized as follows;

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1. Owing to the drawdown of free surface, sliding failure occurred in the upstream fill, the height of failure is 5~10, 9~15, and 13~21(cm) in each model.

2. In consideration of the distribution of pore water pressure Table-5 shows each factor of safety. In the relationship between the drawdown velocity and the factor of safety, it's velocity should be limited to 0.21~0.28(cm/sec), according to each models. In the relationship between the factor of safety and the hydraulic gradient within the upstream slope, it's gradient must be below 0.36~0.43.

1. Introduction

When water flows through the void of embankment in earth structures such as levee, resevoir, earth dam, the infiltration phenomena in the embankment influences the stability of slope. In this case, the downstream slope is influenced by the steady seepage. When the water level is suddenly drawdowned from the top level there could be problems in the stability of the embankment.

The variation of the free surface by this sudden drop of the water level causes a change in the forces on the embankment, and the submerged unit weight below the free surface turns into the total unit weight, therefore, the weight of the soil mass increases. Then the stress in the embankment, especially the pore water pressure is changed and depending on the potential slip surface, the frictional stress decreases, so there is some problems in the stability of the embankment. For the purpose of studying these phenomena, experimental models have been built with sands in the laboratory. When the water level is high and the flow through the embankment is steady, the infiltration phenomena, was observed. The infiltration phenomena at various water levels and the shape of failure arc were determined. At the same time, this paper intends to study the failure slip surface, the relationship between the drawdown velocity and the factor of safety, and the relationship between the hydraulic gradient and the factor of safety.

2. Procedure for Approximation

For particular trial values of the two variables F and θ, corresponding values will be required for the external force Z_N and the external moment M_N to stabilize the embankment. The method of solution is a process of successive approximation in which the value of Z_N and M_N are gradually reduced to a neglibile level.

The process is as follows.

(1) A range of values is chosen for k, one for each inter-slice boundary.

(2) Trial values are chosen for F and θ.

(3) The slope δ of each inter-slice force is then computed using $\delta = k_i\theta$.

(4) The stability equation for force is then used to determine the value of each inter-slice force in turn until the last slice is reached and the value of Z_N is obtained. The value of F is then adjusted by successive approximation, until Z_N is negligible.

(5) Using the values of the inter-slice forces obtained in the final phase of Eq. (4) and substituting in the stability equation for moment the value of M_N is founded. The value of θ is then grad- ually adjusted until M_N is negligible.

(6) Using the values of F and θ obtained from the phase (4) and (5), the process is then repeated from the phase (3) until the changes in F and θ become negligible. This process is

illustrated in Fig. 1.

Owing to the shapes of curve I and II convergence is rapid and lead to the values F_i and Q_i which satisfy both force and moment equilibrium conditions and corresponding to intersection of the two curves.

3. Experimental Method.

This experiment was performed under different experimental conditions according to each model. The object of tests was to estimate the pore pressure and effective stress in embankment. For a given variation of free surface, it is necessary to observe the position of exit point, the shape and height of failure occuring in the slope of embankment when the free surface is varied to accomplish this. The models which were built in the laboratory, are divided into three types according to the shape of their slopes. The basic experimental model is that the downstream slope is constant and slopes 1.00 vertical to 2.50 horizontal whereas the upstream slopes vary from 1.00 to 2.00, 1.00 to 1.75 and 1.00 to 1.50. In allowing water to flow into the embankment model, the inflow velocity was maintained small enough so as not to cause piping. At the top water level the flow must be steady seepage, and when the water level is suddenly dropped according to the experimental condition, the shape of free surface can be observed by measuring the height of water level in each model.

The condition of the experiment is shown in Table 3. Under this experimental condition, the following is obtained in this study: the shape of free surface (when water levels in each slope is 40cm, and 10cm), the position of exit point, and the shape and height of failure plane.

The material which is used in each model is sand and its size is smaller than 2mm and larger than 0.06mm in diameter (See Fig. 2, Table 1) since sand being smaller than 0.06 in diameter can be moved by seepage forces,

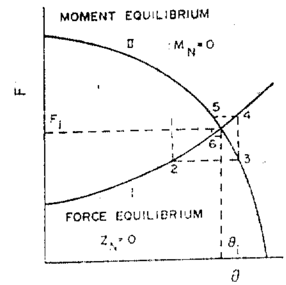

Fig. 1. Method of Solution.

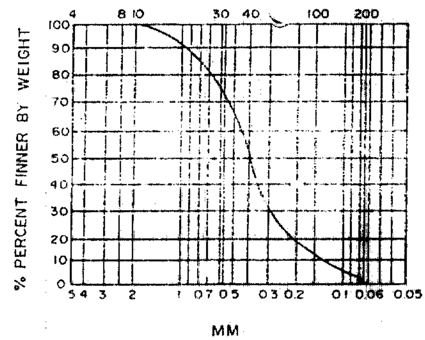

Fig. 2. Grain size accumulation curve.

Table 1. Properties of the material of embankments.

Property	Value
e : void ratio	0.61
n : porosity	0.38
G : specific gravity	2.60
ϕ : angle of internal friction	30°30′
K : permeability	4.51×10^{-2}(cm/sec)
γ_t : total unit weight	1.90
γ_{sat} : saturated unit weight	2.00
γ_{sub} : submerged unit weight	1.00
γ_w : unit weight of water	1.00
w : natural water content	25(%)

Table 2. Angle of slope in each model.

Model	Upstream Slope	Down stream Slope
Model A	1 : 2.0	1 : 2.5
Model B	1 : 1.75	1 : 2.5
Model C	1 : 1.5	1 : 2.5

Table 3. Experimental condition

Slope	Case	V_d(cm/sec)
1.00 : 2.00	case 1	0.10
	case 2	0.19
	case 3	0.23
1.00 : 1.75	case 1	0.12
	case 2	0.20
	case 3	0.25
1.00 : 1.50	case 1	0.15
	case 2	0.23
	case 3	0.28

they are excluded. And this experiment is conducted keeping the embankment being as homogenuous as possible.

4. Results of Experiment and Discussions

4-1. The Shape of Free Water Surface Related to the Slope Embankment, and Water Level during drawdown.

The stability of an embankment under the conditions of through seepage was examined in this study. The stress is changed according to the water level at drawdown. Especially the pore pressure and the effective stress play an important role in the stability analysis of embankment and the location of the slip surface. In this case, it is necessary to determine the exact distribution of the pore pressure with respect to a moving free surface. For this purpose, in accordance with experimental con dition, the head water level was estimated in each model. Table 4 shows its results indicates the shapes. These factor that influences the stability of embankment at drawdown will be treated later. In this experiment, the water level is also found when the direction of free surface is altered and its results are shown in Table 5. This experiment shows that as the slope of embankment becomes less, so its water level becomes lower and as the slope gets

Table 4. The height of free surface from bottom(cm)

Slope	drawdown velocity	water level \ horizontal distance	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210
1 : 2		40							40.6	36.5	35.0	33.8	32.5	31.0	29.5	27.9	26.1	24.5	21.0	17.5	13.5	10.0
	0.10	10	10.0	12.4	14.6	16.5	17.9	18.5	19.0	19.8	19.8	20.0	19.3	18.7	17.3	16.6	15.5	14.6	13.6	12.8	11.5	9.2
	0.19	10	10.0	13.1	15.7	17.5	18.8	19.4	20.5	20.9	21.2	20.8	20.2	19.2	17.5	16.5	15.3	14.5	13.4	12.9	11.6	9.8
	0.23	10	10.0	13.5	17.0	18.8	19.8	20.3	21.0	21.0	22.0	22.3	22.3	22.0	21.0	19.4	17.1	15.1	13.9	13.1	7.8	9.8
1 : 1.25		40						40.0	37.1	35.5	33.6	32.8	30.5	28.5	26.5	24.8	22.5	20.0	16.5	14.0		
	0.12	10	10.9	13.5	15.6	16.8	17.5	18.0	18.4	18.5	18.7	18.5	18.0	17.3	16.3	16.0	15.1	14.1	12.9	11.5	11.0	
	0.20	10	11.0	14.0	16.5	17.7	18.8	19.5	20.0	20.3	20.6	20.0	19.5	18.5	17.8	16.9	16.0	15.0	13.1	11.5	11.0	
	0.25	10	11.2	15.0	17.4	18.6	20.1	20.9	21.7	22.1	22.4	21.0	21.0	20.1	19.1	18.1	17.1	16.0	13.9	11.8	11.3	
1 : 1.5		40					40.0	37.5	35.9	33.8	32.0	30.0	28.1	25.9	23.8	21.8	19.4	15.8				
	0.15	10	10.8	13.9	16.1	17.5	18.5	19.5	19.8	19.6	19.4	19.1	18.8	18.4	17.5	16.3	15.0	13.2	12.0			
	0.23	10	11.1	14.5	16.8	18.3	19.5	20.5	21.0	20.7	20.5	20.2	19.7	19.5	18.0	16.8	15.5	13.5	12.0			
	0.28	10	11.7	15.1	17.8	19.5	20.5	21.7	22.5	22.3	22.0	20.8	20.0	18.8	17.2	16.0	14.7	14.2	12.1			

*drawdown velocity : (cm/sec) *horizontal distance : (cm) *water level : (cm)

Table 5. Water level which is changing the flow direction in free surface.

slope	case	water level(cm)
1.00 : 2.00	case 1	28.7
	case 2	30.3
	case 3	31.0
1.00 : 1.75	case 1	29.4
	case 2	31.2
	case 3	33.0
1.00 : 1.50	case 1	30.2
	case 2	34.5
	case 3	36.3

steeper, so its water level becomes higher, therefore the stability of slope is greatly affected by drawdown velocity.

4-2. The Shape and Height of Failure Surface Influenced by Free Water Surface During Drawdown

By observing the water level as drawdown occurs, the factors such as the forces acting on embankment, the weight of embankment, and the changing pore water pressure influence on the stability of embankment. The embankment could reach failure because of the increases in the pore pressure. As the changing pore water pressure is influenced by the free surface, and the frictional stress between particles on the upstream slope is decreasing, therefore sliding failure takes place when a limit of drawdown velocity reaches a certain velocity. In this case, the results of analysis show that the height of the failure is 5～10cm, 9～15cm, and 13～21cm, as the slopes are 1.00 : 2.00, 1.00 : 1.75, and 1.00 : 1.50, respectively(See Table 6). The shape of failure describes a gentle parabola and the drawdown velocity should be limited to 0.078～0.035(cm/sec) depending on the slope of the embankment.

Table 6. Failure height in each model.

Slope	Case	Failure Height (cm)
1.00 : 2.00	case 1	5.0
	case 2	6.9
	case 3	10.0
1.00 : 1.75	case 1	9.0
	case 2	11.8
	case 3	15.0
1.00 : 1.50	case 1	13.0
	case 2	16.6
	case 3	21.0

4-3. Influence of the Pore Water Pressure with The Drawdown of Free Water Surface

In approximating stability of embankment by finding the exact point of action of the inter-slice force, the location of the slip surface can be determined. The point of action of thee inter-slice force is changed according to the variation of free surface and due to change the pore pressure. By knowing the change in distribution of the pore water pressure and determined inter-slice force, the point of action was determined. The variation of free surface which is based upon each experimental condition can be seen in Table 4. In this case, in the typical slice of embankment, the magnitude of the force D and the boundary due to the pore pressure will be and the force will act at the height $H/3$ above the lower end of the boundary (See Fig. 3). Z is the total inter-slice force and acts at the angle to the horizontal at a distance L from the bottom of the boundary. Z' is a vertical component expressed as an effective stress and acts at a distance L' from the bottom. It is $Z\cos\delta - D$. And S_V is the tangential component of Z. Taking moment about B in Fig. 3.

$$\frac{D'}{H'} = \frac{L}{H}\left(\frac{Z\cos\delta - D/3\,L/H}{Z\cos\delta - D}\right)$$

The position of the potential slip surface can be obtained with the above formula. The result of the factor of safety according to the process of solution has been already explained, and appears in Table 7. According to the comparision between the factor of safety by this process and the factor of safety by Bishop's method, it is shown that the former is about 3.8~4.3% lower than the latter.

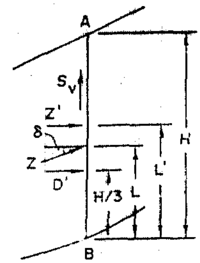

Fig. 3. Force on an inter-slice boundary.

Table 7. Factor of safety.

Slope	Case	F	
		Author	Bishop
1.00 : 2.00	case 1	1.47	1.51
	case 2	1.33	1.37
	case 3	1.11	1.18
1.00 : 1.75	case 1	1.30	1.42
	case 2	1.21	1.28
	case 3	0.93	1.14
1.00 : 1.50	case 1	1.23	1.33
	case 2	1.01	1.19
	case 3	0.78	0.86

Table 8. Hydraulic gradient in each model.

Slope	Case	Hydraulic gradient
1.00 : 2.00	case 1	0.24
	case 2	0.31
	case 3	0.35
1.00 : 1.75	case 1	0.31
	case 2	0.36
	case 3	0.48
1.00 : 1.50	case 1	0.39
	case 2	0.45
	case 3	0.51

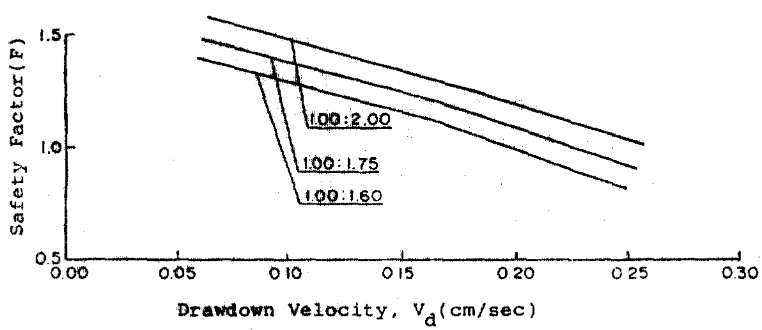

Fig. 4. Relationship between factor of safety(F) and drawdown velocity, (V_d(cm/sec))

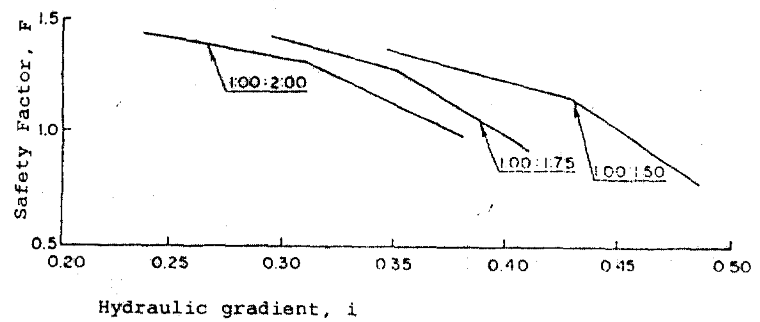

Fig. 5. Relationship between factor of safety(F) and hydraulic gradient(i)

4-4. Relationship between the Drawdown Velocity and the Factor of Safety

In the upstream fill, when the water level is suddenly dropped, this change of the free surface will cause a change in the direction of flow. This direction will be towards the upstream slope and in the downstream slope it will remain toward the downstream face. The direction of action of seepage pressure will also be changed. At this time, the position of the free surface is the same as previously found. The upstream and the downstream slope can be considered separately. According to drawdown velocity, the stability of slope in the upstream will be critical. Table-4 shows the changing aspect of free surface as influenced by drawdown velocity. Taking the pore water pressure into consideration for each model, the factor of safety at three different slopes is shown in Table 7.

In this study, the relationship between the factor of safety and the drawdown velocity (V_d) shows that as the drawdown velocity increase the factor of safety is respectively lowered (See Fig.-4). In the case of considering the stability of upstream slope, the drawdown velocity becomes unstable when it is over 0.21~0.28(cm/sec). Therefore, the drawdown velocity should be limited to this range. In the upstream fill, in the time of considering the flowing direction of free surface, and exit point is made in this slope. In this time, the stability of embankment can be understood in relation to hydraulic gradient which is related with the free surface. In the level being cosidered hadraulic gradient (i) in each case indicated in Table 8. Here, the factor of safety is sensitively changed according to the change of hydraulic gradient (See Fig.-5). At this time, the limit of hydraulic gradient for the stability must be below 0.36~0.43.

5. Conclusion

In the study, the main points investigated were as follows: the stability analysis by infiltration phenomena according to each model, the failure slip surface according to the drawdown velocity of water level, the factor of safety, and other elements affecting the stability.

1. Owing to the drawdown of free surface by sudden drop, the sliding failure occured in the upstream fill. In this case the shape of failure is a gentle parabola and the height of failure was 5~10, 9~15, and 13~21(cm) in each model.

2. When considerating the distribution of pore water pressure on the free surface, the factor of safety is 3.8~4.3% lower than by Bishop's method.

3. In the relationship between the drawdown velocity and the factor of safety, the velocity affects the stability of embankment. Because the factor of safety decreases with increasing drawdown velocity, the drawdown should be limited to 0.21~0.28(cm/sec), depending on each slope of embankment.

4. In the relationship between the hydraulic gradient within upstream fill according to the drawdown of free surface and the factor of safety, the factor is considerably lowered by increase of the hydraulic gradient and in order to stabilize embankment, the hydraulic gradient must be below 0.36~0.43.

Reference

1. Baker, R. and M. Garber, "Variational Approach to Slope Stability," *Proc. Ninth, Conf. Soil Mechanics*, Tokyo, 1977, pp. 9~13.
2. Bishop, A.W., "The Stability of Earth Dams",

Ph. D. Thesis, University of London, 1952, pp. 94~117.

3. Bishop, A.W., "The Use of Slip Circle in the Stability of Earth Slopes", *Geotechnique,* 1965, pp. 7~17.
4. Bishop, A.W., "The Use of Slip Circle in the Stability Analysis of Slopes", *Geotechnique, London, England,* 1971, pp. 432~456.
5. Bishop, A.W., "The Influence of Progressive Failure on the Method of Stability Analysis", *Geotechnique, 21,* 1971, pp. 168~172.
6. Casagrande, A., "Seepage through Dams", *Journal, New England Water Works Associations LI,* 1937, pp. 131.
7. Castillo, E. and A. Luceno, "Critical Analysis of some Variational Methods in Slope Stability Analysis", *Geotechnique, 6,* 1982, pp. 195~209.
8. Dorfman, A.G., "Variational Method of Investigation of the Stability of Slopes", *Geotechnique Transport, 21*(9), Moscow 1965, pp. 22~41.
9. Fellenius, W., "Calculation of the Stability of Earth Dams," *Trans. Sweden Cong. on Large Dams 4,* Washington 1963.
10. Garber, M., "Variational Method of Investigation of the Stability of Slopes," *Soil Mechanics and Foundation Engineering, 10,* (1), 1973, pp. 77~87.
11. Janbu, N., "Application of composite Slip Surfaces for Stability Analysis", *Proc. European Conf., Of Stability of Earth Slopes,* 1954, pp. 34~60.
12. Janbu, N., "Stability Analysis of Slopes with Dimesionless Parameters," *Harvard Soil Mechanic Series (46),* 1954, pp. 81~96.
13. Morgenstern, N., "Stability Charts for Earth Slopes During Rapid Drawdown? *Geotechnique, 13*(1), 1963, pp. 121~131.
14. Morgenstern, N. and V.E. Price, "The Analysis of the Stability of General Slip Surfaces," *Geotechnique, 15,* 1966, pp. 79~93.
15. Morgenstern, N., "Stability Charts for Earth Slopes During Rapid Drawdown," *Geotechnique, 13*(2), 1963, pp. 246~272.
16. Noveiller, E., "The Stability Analysis of Slopes with Slip Surface of General Shape," *Proc.6th ICSMFE, Montreal, 2,* 1965, pp. 525~552.
17. Revilla, J. and E. Castillo, "The Calculus of Variation Applied to Stability of Slopes," *Geotechnique,* 27, 1977, pp. 1~11.
18. Schmid, I., "DreWasserbewegung in Dammkorper," *Julius Springer,* Berlin, 1928.
19. Shin, B.W., "A Study of the Analysis of Stability of Slope and Embankment," *K.S.C.E.,* 1983, pp. 9~18.
20. Skempton, A.W., and A. Bishop, "The Pore Pressure Coefficients in Practice," *Geotechnique, 4,* 1954, pp. 143~153.
21. Szendiei, M.R., "The Computation of Subsurface Drainage Conditions," *National Institute of Road Research, South Africa, Pretoria, RS 6171,* 1971, pp. 16.
22. Taylor, D.W., "Stability of Earth Slopes," *Contributions to Soil Mechanics, Boston Society of Soil Eng. 24(1),* 1937, pp. 337~386.
23. Vollker, R.E., "Nonlinear Flow in Porous Media by Finite Element," *Journal, Hydraulics Division, Proceedings A.S.C.E., 195*(9), 1969, pp. 2093~2114.
24. Shin, B.W., "*A Study of the Seepage through Sand-constructed Model Dam,*" Inha Institute of Technology, 4~18(1979).
25. Shin, B.W., "A Study of the Analysis of Stability of Slope and Embankment," *K.S.C.E.,* 9~18(1983).

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