한국지반공학회논문집 제19권 6호 2003년 12월 pp. 61 ~ 70

A Study on the Behaviour of an Earth and Rockfill Dam Due to Reservoir Water

저수변화에 따른 사력댐의 거동 연구

Shin, Jong-Ho* 신 종 호

요 지

사력댐은 점토부터 사석에 이르는 다양하고 복합적인 재료로 구성되어 있고, 이에 따른 제체의 투수성 차이 등으로 인해 건설 후의 거동양상은 아주 복잡하게 나타난다. 특히, 건설 이후 계절적 강우 차이로 야기되는 수위변화는 댐의 거동변화를 야기하며, 이런 특성들은 결과적으로 건설 후 댐 거동의 정형화를 어렵게 한다. 건설 후 댐의 거동은 저수위의 변화, 제체침투 등으로 인해 시간 의존적이며 이러한 거동이 건설 후 댐의 열화현상과 어떠한 관계가 있는가를 조사해보는 것은 중요한 의미가 있다. 건설 후 댐 거동정보는 댐 관리는 물론 설계에도 아주 유용한 정보로써 활용될 수 있다. 본 연구에서는 건설 후 발생 가능한 다양한 수위변화조건을 담수, 수위하강, 반복수위의 형태로 이상화하고, 수위변화속도에 따른 시간의존성 거동을 모델링하기 위하여 변위-간극수압의 결합방정식을 이용한 유한요소해석을 수행하였다. 해석결과는 하중전이, 수압할렬의 가능성, 응력경로 변화 등의 관점에서 분석하였다. 본 연구결과로부터 실제 댐파괴 사례로부터 발견되는 지반공학적 문제에 대한 정량적 이해와 건설 후 댐관리에 있어 댐에 잔존하는 역학적 능력을 고려하여 수위를 제어하는 것이 중요함을 확인하였다.

Abstract

The behaviour of an earth and rock-fill dam is complicated due to reservoir water and various materials in zoned dams. Different materials with a wide range of permeability and seasonal variation of reservoir water result in the time dependent post-constructional behaviour. In aged dams it is often required to control water level to keep the dams safe. In this case information on the post-constructional dam behaviour is important. However, present geotechnical knowledge does not fully support the occasion. In this study the post-constructional behaviour of a dam is investigated using coupled finite element models for series of idealized water reservoir cases: impoundment, draw down, seasonal fluctuation with different rising and falling speeds. Numerical results were analysed in respect of geotechnical parameters such as load transfer, hydraulic fracturing potential and stress paths. It is shown that the control of water level is an important factor while operating dams.

Keywords : Coupled analysis, Earth and rockfill dam, Reservoir water

1. Introduction

It has been repeatedly reported that the geotechnical problems are the main sources of the failure of embankment dams. Generally the types of failures can be categorized into two groups: the occurrence of crack accompanying piping erosion, and slidings due to the reduction of shear strength. Apparently both types of

---

* Member, Director, Office of Cheonggye-Cheon Restoration, Seoul Metropolitan Government, jongho-shin@hanmail.net

failures are related with seepage water from the reservoir. The effect of interaction between dam and reservoir water would be significant in the post-constructional dam behaviour.

The variation of water level causes loading and unloading in the upsteam shell, particularly at the upstream face of the core, and high strength mobility. Consequently, stress redistribution and reorientation are taking place in dam, which in turn affect potential dam failure. Such examples can be found in the past dam failures during impoundment and rapid draw-down.

Facts mentioned above envision that the deterioration of an embankment dam in the long term is also associated with the changes of reservoir water. Although there are only qualitative comments on the post-constructional failures of dam while water level has changed, these are mainly based on the limited experience of dam. Initial impoundment or rapid draw-down also implies the significance of changing speed of water level. However, quantitative research on the subject is rare, as there are many influencing factors which make it difficult to model the dam behaviour after construction.

So far most research on dam behaviour has been mainly focused on the behaviour during construction. Post-constructional behaviour is less studied, as the boundary conditions are so complicated that the analysis requires sophisticated mathematical tools.

In this study a coupled finite element method is adopted to simulate the post-constructional dam behaviour. The variation of water level is idealized by considering three cases which represent impoundment, draw-down and seasonal fluctuation with different speeds of rising and falling of reservoir water level. Speed means time to require for the water level to reach a desired level. So time also affects the inherent pore water pressure of the core since the end of construction.

2. Geotechnical Consideration of Dam Modelling

It is convenient to categorize dam behaviour into two stages with respect to modelling: constructional and post-constructional. Post- constructional behaviour is to start from the initial impoundment. Afterward, seasonal changes of water level and draw-down during operation could be the main sources of post-constructional dam behaviour. Consequently, the behaviour is time dependent. Interaction between reservoir water and dam is so complicated that the modelling of dam requires special geotechnical consideration. While the water level is rising up, the permeable upstream soils(shell materials) are submerged, and will be affected by a buoyant force. In addition, the reduction of volume is caused by wetting. Static water pressure acts on the upstream face of the core of which permeability is much lower than that of shell materials(Kovacevic, 1994). The effect of wetting is not significant and neglected in this study.

In normal finite element procedure, the effect of reservoir water in the shell materials are modelled by considering the difference of unit weight before and after submerging. Equation(1) represents the range of variation of unit weight in the shell.

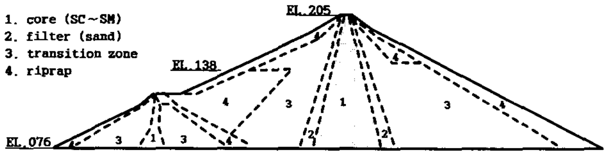
$$\pm\Delta\gamma=(\gamma_{sat}-\gamma_{sub})\sim(\gamma_t-\gamma_{sub}) \qquad (1)$$

in which the γ_{sat} is the saturated unit weight, the γ_{sub} is the submerged one, the γ_t is the total unit weight.

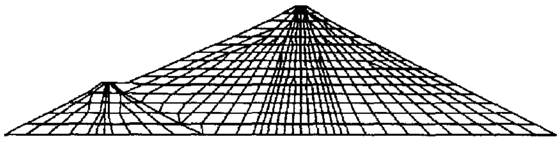
In the upstream shell, the speed of water level change is normally slower than the seepage velocity. Thus it is possible to assume that the shell material can be considered as fully permeable. There is little transient effect in the shell. On the other hand, reservoir water imposes static water pressure on the upstream face of the core initially. With time seepage will take place through the core. This behaviour is time-dependent, and modelling requires coupled equation. In this study a coupled analysis scheme adopting the Biot's equation(1941) was used(Potts & Zdrakovic, 1999; 2001). The homonized pore fluid concept(Chang & Duncan, 1983) was used to treat partly saturated flow.

3. Analysis Model and Boundary Conditions

The dam profile to be analysed is shown in Figure 1(a).



(a) Dam profile



(b) Finite element descretization

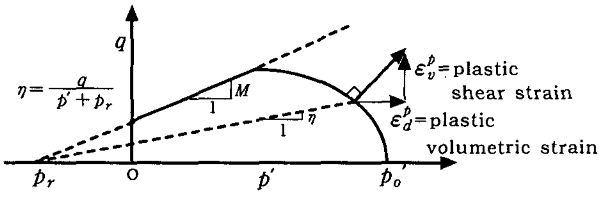
Fig. 1. Dam profile and finite element descretisation

It is a zoned earth and rockfill dam with a core in the center. The dam has a maximum height of 129m above stream bed and founded on relatively hard rocks which is grouted. Details of the dam are not fully commented in this paper, as the analyses are not necessarily related to any specific dam, and are mainly to investigate the effect of reservoir water by a numerical model. Only some comparisons were made to verify the validity of the analysis scheme.

Finite element descretisation was made by considering soil profile, construction sequence (i.e. layered construction) and consideration of water level changes for modelling of reservoir water presented in Figure 1(b). It was assumed that a resonable approximation to the behaviour could be obtained by performing a plane strain analysis of a typical section.

4. Soil Models

The extended modified Cam-clay model was used to represent soil behaviour(Duncan *et al.*, 1981). In this model an isotropic elastic behaviour is assumed before yielding of soil. The model satisfies normality and employs an associated flow rule. It is known that the modified Cam-clay model is appropriate in the modelling of normally and lightly over-consolidated clay(Lade & Duncan, 1973). In general elliptical yield surface overestimates the soil strength in the left side of the critical state(dry side). This drawback is partly improved by using linear failure surface as shown in Figure 2. A modified CON2D which was originally developed by Duncan *et al.* (1981) was used.



$$p' = \frac{1}{3}(\sigma_x' + \sigma_y' + \sigma_z')$$

$$q = \sqrt{\frac{1}{2}\left[(\sigma_x' - \sigma_y')^2 + \sigma_y' - \sigma_z')^2 + \sigma_z' - \sigma_x')^2\right]}$$

Fig. 2. Yield surface of the Extended Cam-clay model

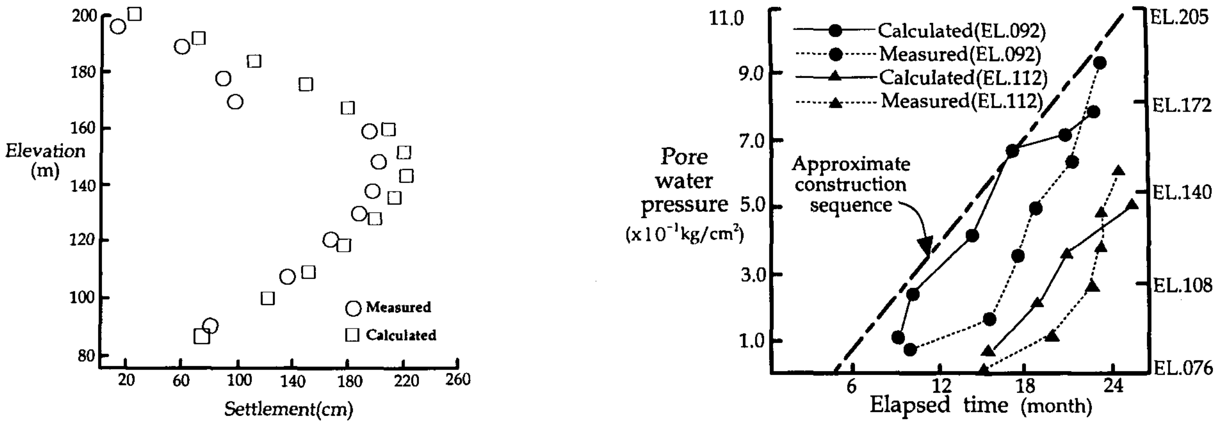
Table 1. Soil parameters

Parameter	Core		Shell			
	SC~SM		Sand & Gravel		Rockfill	
γ_t (t/m^3)	2.04		1.88		2.30	
p_r (t/m^2)	10.44		10.44		10.44	
p_o' (t/m^2)	3.10		0.00		1.04	
x	0.0058		0.0059		0.0058	
M	0.79		1.55		1.71	
$k_h(m/year)$	15.8		3154.0		3154.0	
$k_v(m/year)$	6.3		3154.0		3154.0	
p_{oave} − λ	p_{oave}	λ	p_{oave}	λ	p_{oave}	λ
	44.06	0.026	32.95	0.026	30.50	0.0069
	76.19	0.068	100.2	0.044	68.44	0.0272
	135.6	0.096	179.9	0.066	130.4	0.0581
p' − ν	p'	ν	p'	ν	p'	ν
	10.2	0.32	10.2	0.15	10.2	0.29
	30.6	0.37	30.6	0.32	30.6	0.33
	61.2	0.41	61.2	0.39	61.2	0.37

Nonlinearity of the dam materials is considered by allowing prescription of stress dependent soil parameters. Soil parameters for the post-constructional analysis are evaluated based on the design and safety analysis reports of the reference dam. However, some manipulations were made to avoid misunderstanding of the dam. Parameters used are summarized in Table 1. The γ_t is unit weight, p_r and p_o' are defined in Figure 2, M, x and λ are the Cam-clay model parameters, k_h and k_v are soil permeability, p_{oave} is average mean effective stress, ν is the Poison's ratio.

5. Analysis of Construction

Although this study is to investigate the post-



(a) Displacement at the center of the core

(b) Pore water pressure at the center of the core

Fig. 3. Results of construction analysis(end of construction)

constructional behaviour of a dam due to changes of reservoir water, it is required to perform construction analysis to establish initial stress condition for further analysis. To simulate construction sequence layered analysis scheme is adopted. As shown in Figure 1(b), the section of the dam is divided into 20 steps including 5 steps for the copper dam.

Construction analysis was carried out with coupled finite element scheme. As the core is unsaturated material, a modelling of pore water development scheme proposed by Chang & Duncan(1983) was used. Zero displacement and impermeable boundary condition at the foundation level is prescribed. Only the core material is considered as consolidating.

Figure 3 shows that the calculated results slightly overestimated the displacement at the center line of the core, however, the difference is not significant. Pore water pressures are underestimated by $1\sim2kg/cm^2$ at the end of construction. A time lag during initial stage of construction is seemed to be appeared. Generally the difference can be caused by the limitation of modelling in hydraulic boundary conditions and permeability modelling of unsaturated soils. In addition, the reliability of measurement is also attributed to the possible difference. However, a close look at the data shows that general trends are likely to be the same, which indicates the modelling methodology used in this paper is generally acceptable. In this paper the calculated results are used as those of an initial state of post-constructional analyses.

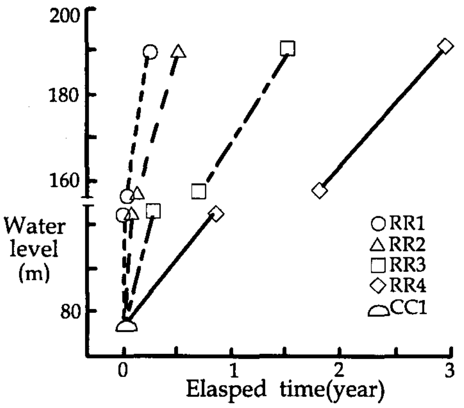
6. Analysis of Post-constructional Behaviour

Changes of reservoir water can be characterized into

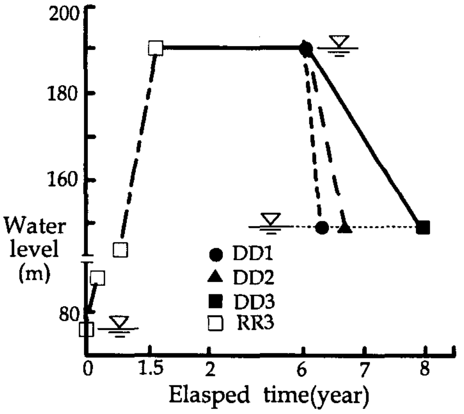
Table 2. Analysis cases

Case		Key	Load steps	Duration (year)	Change of Water level	Symbol	Initial condition
construction		CC1	20	3.60		⌓	
impoundment	very rapid	RR1	1	0.25	EL76→EL190 (+114m)	○	immediately after construction
	rapid	RR2	1	0.50		△	
	moderate	RR3	1	1.50		□	
	slow	RR4	1	3.00		◇	
draw-down	very rapid	DD1	3	0.25	EL190→EL150 (−40m)	●	after impoundment with normal speed
	rapid	DD2	3	0.50		▲	
	slow	DD3	3	2.00		■	
fluctuation	steady state	WW1	2	5.00	EL174	⊙	constant water level after impoundment with normal speed
	seasonal fluctuation	WW2	11	2x0.5/ Cycle	EL190↔EL158 (±32m)	◎	

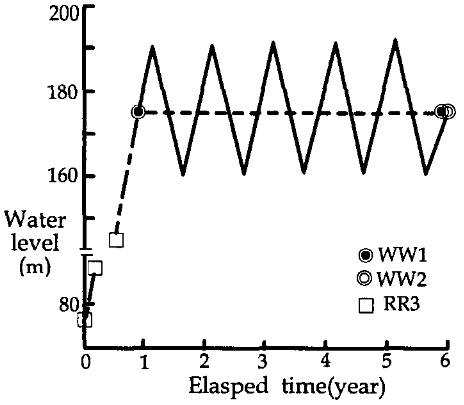
three types: impoundment, draw-down and long term seasonal fluctuation. Impounding is one of the most important occasions. Significance of the first impounding is highlighted from the past experience of dam failures. Draw-down of reservoir water is also an important factor. Rapid draw-down is generally taking place by opening water gate. Seasonal changes of water level also influence the behaviour in the long term.



(a) Impounding(4 cases)



(b) Draw-down(3 cases)



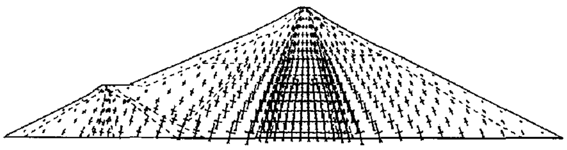
(c) Seasonal fluctuation(2 cases)

Fig. 4. Analysis cases simulating water level changes

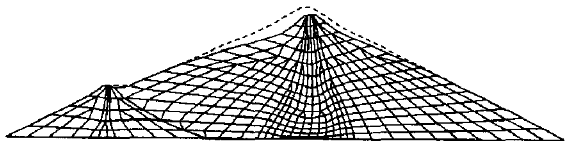
Four cases of impoundment and three cases of draw-down with different speeds are considered. Water level fluctuation is modelled by considering 5 cycles with the period of a year of seasonal variation. For comparison constant water for 5 years is also analysed. Table 2 summarizes all cases analysed in this study. They are also presented graphically in Figure 4.

7. Results of Analyses

An initial state of stress for the post-construction analysis is inherited from the construction analysis. Figure 5 presents typical long term behaviour(WW1). It has found that the rotation of principal stress due to reservoir water is not significant, however, long term deformation shows some volume loss. This results provide intuition for determining reference location for the analysis of the numerical results.



(a) Orientation of principal stresses



(b) Dam deformation(volume loss)

Fig. 5. Typical results(WW1:long term)

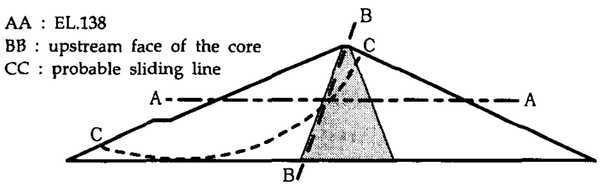


Fig. 6. Reference elevation and lines

It will be convenient to establish reference location and elevation to compare the effect of reservoir water. Construction and post-constructional analyses showed that elements adjacent to the interface of the core and the shell at around EL.138 experienced large amount of stress change. Therefore, the stresses of the elements near those locations are chosen as reference values.

The post-constructional analyses traced load transfer ratio(LTR) and stress path for different cases of reservoir water changes. In this study the LTR is defined as a ratio of vertical stresses at the center of the core and the filter.

$$\mathrm{LTR} = \frac{\sigma_{yc}'}{\sigma_{yf}'} \tag{2}$$

where σ_{yc}' and σ_{yf}' are the effective stresses at the center of core and filter respectively. When the LTR is greater than 1.0, the stress transfer from the shell to the core is taking place.

Hydraulic fracturing potential(HFP) is also investigated. The HFP is quantified as a ratio of effective minor principal stress to unbalanced pore water pressure(Penman, 1986). Mathematical expression of the parameters are as belows:

$$\mathrm{HFP} = \frac{(\sigma_3 - \Delta u)}{\Delta u}\ , \quad \Delta u = u_s - u_e \tag{3}$$

where u_s is the hydrostatic water pressure and u_e is the excess pore water pressure at the center of nearest elements of the interface. If HFP is greater than 1.0, net water pressure exceeds minimum principal stress, which would cause cracks allowing reservoir water to flow in them.

8. Effect of Initial Impoundment

During initial impounding the upstream shell and the filter experience a considerable reduction in effective stress due to the buoyant force. On the other hand, hydrostatic pore water pressure is acting on the upstream face of the core. The combined effects cause complicated dam behaviour. It is shown that the resultant stress of the core is smaller than those at the end of construction, which indicates that the effect of buoyant force acting on the upstream shell is more influencing than that of hydrostatic water pressure.

Stress paths show this behaviour evidently. Figure 7 presents the effective stress paths for the elements near interface at the elevation of 138. Possibly the actual stress paths could be curved lines due to the time-dependent effect of dissipation of excess pore water pressure. However, linear paths are assumed for simplification.

The core elements undergo expansion of volume as σ_3 and σ_1 decrease on the basis of principal stress axes, meanwhile the shell elements experience axial expansion as σ_1 decreases without significant change of σ_3. Stress state of the core elements moves to safe side, while the stresses of filter elements approach failure line.

Figure 8 presents the vertical stresses on the elevation of 138 immediately after initial impoundment from EL.76 to EL.190. In the upstream shell considerable reduction in stress has appeared, however, the core experiences little change. It is interesting to note that the stresses in the downstream shell have increased after impoundment. Although the effect of filling speed is not significant, it is found that the faster filling causes somewhat smaller stress in the core.

This effect is also investigated in terms of load transfer. Variation of LTR due to filling is not significant as shown in Figure 9. Load transfer from the core to the shell is still taking place, however, there is no general trend along

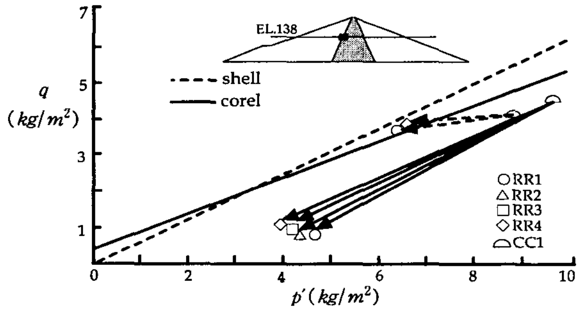


Fig. 7. Stress paths during impoundment(EL.138)

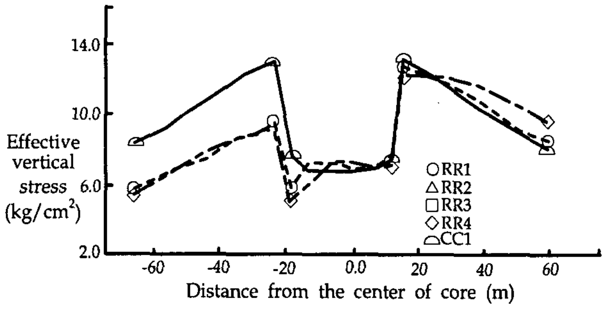
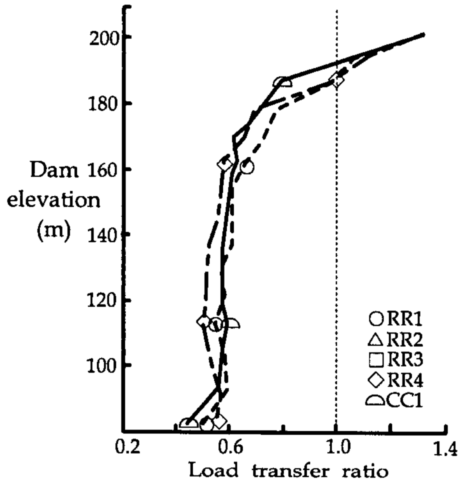


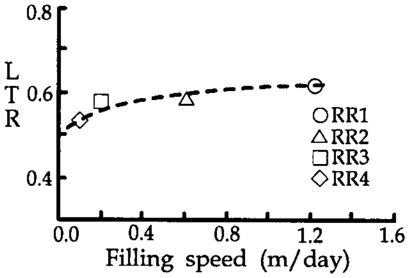
Fig. 8. Effective vertical stresses after impounding(EL138)

the line BB in Figure 6 as shown in Figure 9(a). Faster filling has resulted in more stress reduction in the shell than in the core. Consequently, it was shown that increase in filling speed caused only slight reduction in load transfer at the elevation of 138 as presented in Figure 9(b).

Hydraulic fracturing potential(HFP) is another geotechnical concern in earth and rockfill dam. To evaluate the potential unbalanced water pressure, ($u_s - u_e$) and minor principle stress, σ_3, are examined. HFP with filling speed is shown in Figure 10. Faster filling leads to larger unbalanced water pressure at the interface between the shell and the core which indicates high vulnerability to HFP.



(a) LTR with the dam height(line BB in Figure 6)



(b) LTR (EL138)

Fig. 9. Load transfer due to impoundment with filling speeds

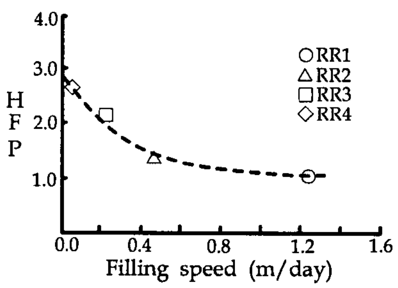


Fig. 10. Hydraulic fracturing potentials with filling speeds(EL.138)

9. Effect of Draw-down

Draw-down is likely to result in complete reversal of the impoundment. It is modelled by removing buoyant force and hydrostatic pressure on the upstream face of the core. The shell material is designated as non-consolidating. However, reduction in strength cannot be modelled appropriately by the numerical method.

After impoundment to EL.190, it is assumed that the reservoir water is drawn down to EL.150. Draw-down cases with different time period of 0.25, 0.5 and 1.0 year are analysed. Stress paths due to draw-down are presented in Figure 11. The elements in the core experience $\Delta\sigma_1 > 0$ and $\Delta\sigma_3 > 0$, $\Delta\sigma_1 \gg \Delta\sigma_3$. Meanwhile the shell elements exhibit $\Delta\sigma_1 > 0$ and $\Delta\sigma_3 > 0$, $\Delta\sigma_1 > \Delta\sigma_3$.

Figure 12 shows the changes of vertical stress at EL.138. It is found that the draw-down has caused a decrease in stress in the upstream shell and the core.

The stress change is represented in terms of LTR along the dam height in Figure 13(a). The LTR decreases

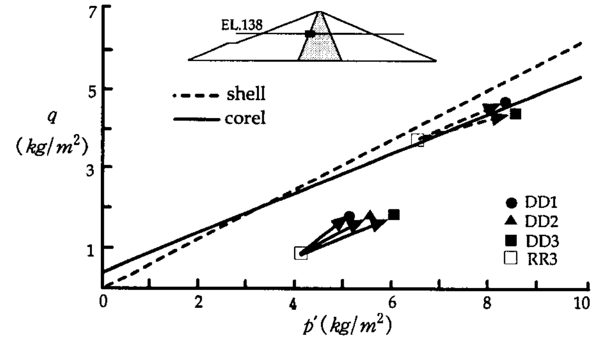


Fig. 11. Stress paths during draw-down(EL.138)

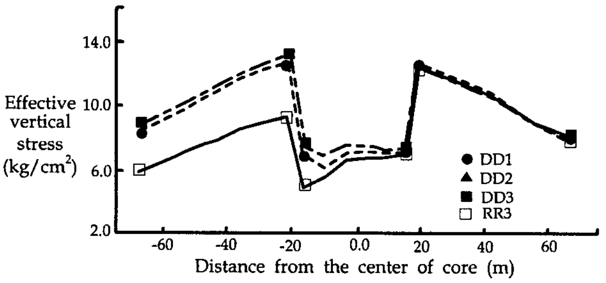
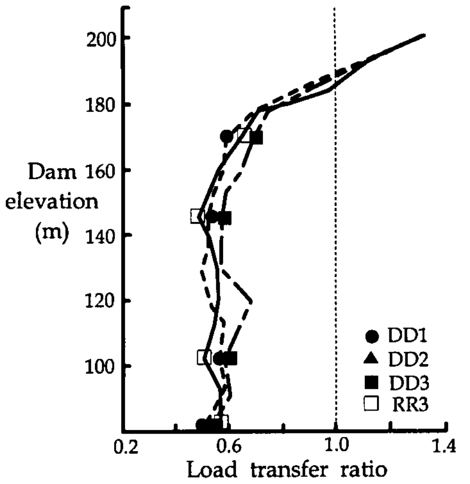
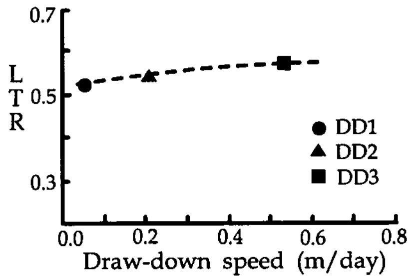


Fig. 12. Stress change due to the draw-down(EL138)

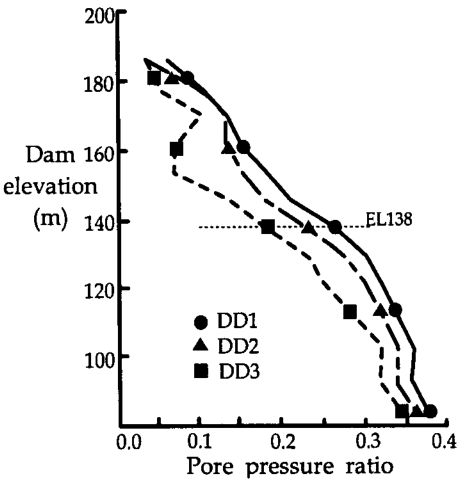


(a) LTR with the dam height(line BB in Figure 6)

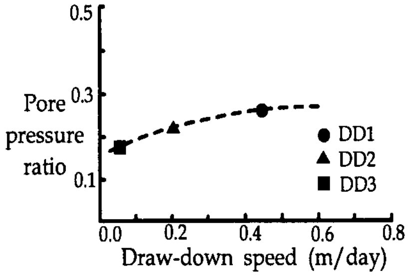


(b) LTR (EL.138)

Fig. 13. Load transfer due to draw-down



(a) Pore pressure ratio with the dam height(line BB in Figure 6)



(b) Variation of pore pressure ratio(EL.138)

Fig. 14. Variation of pore pressure ratio with draw-down speeds

slightly with an increase of draw-down speed. Variation of LTR with draw-down speed at the reference elevation is shown in Figure 13(b).

In the case of draw-down, it is not necessary to examine HFP, since the intrusive external water pressure is zero. Instead, slope stability is likely to be the main geotechnical problem to be checked. Rapid draw-down causes temporary undrained-unconsolidated shear condition. This behaviour is simply examined by evaluating pore pressure ratio at a point of a probable failure line. Generally this behaviour can be considered by assuming undrained shear condition in the shell. However, the speed considered in this study is not rapid to enough cause undrained condition.

The probable failure line obtained by the Bishop's simplified method is shown in Figure 6. The line passes through upstream face of the core around EL.138. Since the Bishop's equation neglects the change of soil properties during draw-down, contribution of pore pressure to safety can be simply investigated by considering pore pressure ratio. In Bishop's simplified method, the safety is proportional to $(1-r_u)$, where the pore pressure ratio, $r_u = \frac{u}{\sigma_y' + u}$. The increase in r_u reduces the safety of slope. Figure 14 presents the distribution of r_u along the line BB in Figure 6 with different draw-down speeds. It is concluded that the safety of a slope decreases with an increase in draw-down speed.

10. Effect of Seasonal Fluctuation

Seasonal fluctuation of reservoir water can cause long term cyclic behaviour. To address the exact cyclic behaviour, an advanced soil model would be required. The extended Cam-clay model seems not to be appropriate to carry out the cumulative cyclic analysis, however, stress dependent non-linear parameter makes it possible to consider the effect approximately. It is assumed that reservoir water fluctuates seasonally from EL.158 to EL.190. The fluctuation case is compared with the case of constant reservoir water for 5 years. Hydraulic fracturing

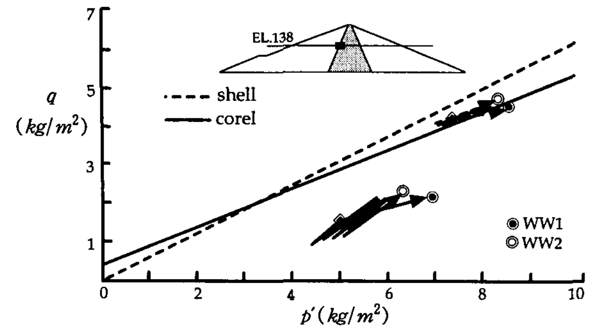


Fig. 15. Stress paths during seasonal fluctuation(EL.138)

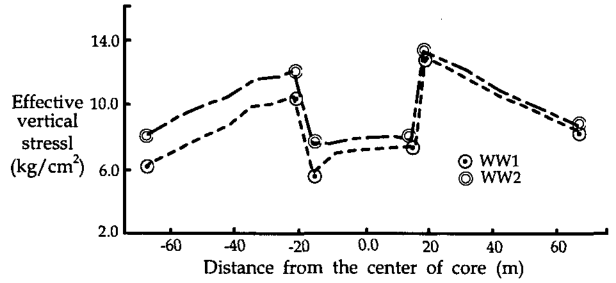
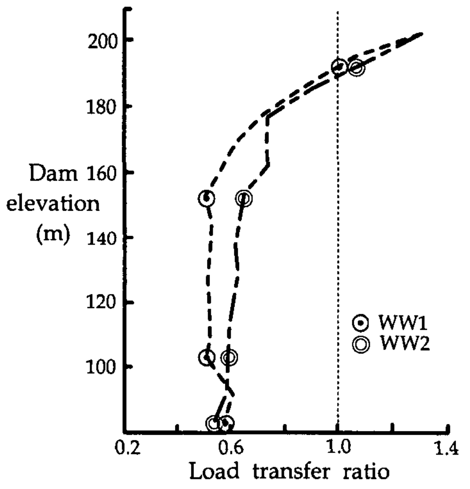
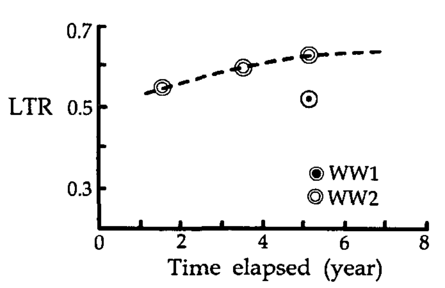


Fig. 16. Stress change due to the seasonal(EL.138)



(a) LTR with the dam height(line BB in Figure 6)



(b) LTR(EL.138)

Fig. 17. Load transfer due to seasonal fluctuation

and slope failure are not considered, as the seasonal changes generally have long term period and low amplitude.

Figure 15 shows the stress paths during fluctuation. Principal stresses have increased in both upstream shell and core, i.e. $\Delta\sigma_1>0$, $\Delta\sigma_3>0$. After 5 years of seasonal fluctuation of reservoir water stress paths have moved to the safe state of stress.

Figure 16. compares the distributions of effective vertical stress at the elevation of 138. Seasonal fluctuation has caused an increase in stresses in both the upstream shell and the core. Behaviour during constant water level only reflects the reduction in pore water pressure.

However, such an increase in stress doesn't increase load transfer; it rather decreases with increasing number of repeat as shown in Figure 17. Therefore, in the long run, it can be concluded that the behaviour of dam tends to be stabilized.

11. Conclusions

Post-constructional dam behaviour is investigated using coupled finite element scheme with the extended Cam-clay model by simulating the reservoir water movement .

Although the analyses performed in this study cannot model all complexity of real dam behaviour, the results have shown a characteristic post-constructional behaviour. Conclusions from the analyses are summarized as belows:

(1) During impoundment, an increase in filling speed reduces load transfer, and an increase of draw-down speed also reduces LTR slightly. It is also identified that seasonal fluctuation has increased LTR.

(2) It is found that faster filling speed causes higher vulnerability to HFP during impoundment.

(3) Qualitative indication for slope stability is obtained for draw-down analyses. Safety of a slope decreases with an increase of draw-down speed.

Post-constructional analyses performed in this study give a few profound understandings for the dam behaviour. This information can be used to control reservoir water during operation, particularly for aged dams. It is also useful to feed back the information into design and construction.

References

1. Chang, C. S. and Duncan, J. M.(1983), "Consolidation analysis for partly saturated clay by using an elastic-plastic effective stress-strain model", *Int Journal for numerical and analytical methods in geomechanics*, Vol.7, pp.39-55.
2. Industrial Base Development Corporation(1987), *Soyang Gang Multi-purpose Dam Behaviour and Safety Analysis Report.*
3. Korea Water Resources Development Corporation(1969), S*oyang Gang Multi-purpose Dam Project*, Design Report.
4. Duncan, J.M., D'Orazio, T.B., Chang, C.S., Wong, K.S. and Namq, L.I.(1981), *Con2D: A finite element computer program for analysis of consolidation*, Univ. of California Berkeley, California, Report No.UCB/GT/81-01, Mar.
5. Kovacevic, N.(1994), *Numerical analysis of rockfill dams, cut slopes and road embankments*, PhD Thesis, Imperial College, Univ of London.
6. Kulhawy, F.H. and Gurtowski, T.M.(1976), "Load transfer and hydraulic fracturing in zoned dams", *Journal of the geotechnical division*, ASCE, Vol.102, GT9, pp.963-974.
7. Lade, P.V. and Duncan, J.M.(1973), "Cubical Triaxial Tests on Cohesionless soil", *Journal of soil mechanics and foundation div.*, ASCE, Vol.99, No.SM10, pp.793-812.
8. Nobari, E.S. and Duncan, J.M.(1972), *Effect of reservoir filling on stresses and movements in earth and rockfill dams*, Univ. of California Berkeley, California, Report No.TE-72-1.
9. Penman, A.D.M.(1986), "Hydraulic Fracturing in zoned earth dams", *Geotechnique* 36, 1986, No.3, pp.303-348.
10. Potts, D.M. and Zdrakovic, L.(1999), *Finite element analysis in geotechnical engineering, theory*, Thomas Telford Publishing.
11. Potts, D.M. and Zdrakovic, L.(2001), *Finite element analysis in geotechnical engineering, application*, Thomas Telford Publishing.
12. Sherard, J.L.(1985), "Hydraulic fracturing in embankment dams", *Journal of the geotechnical div.*, ASCE, May, pp.905-927.

(received on Apr. 15, 2003, accepted on Nov. 24, 2003)