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ON ANALYSIS OF THE BEHAVIOR OF AN EMBANKMENT DAM DURING THE FIRST IMPOUNDMENT OF RESERVOIR USING AN ELASTO-PLASTIC MODEL FOR UNSATURATED GEOMATERIALS

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ABSTRACT

In order to obtain substantial information for maintenance of embankment dams, studies focusing future behavior of dam embankment have been carried out before the commencement of the first impoundment of reservoir. Nowadays it is common to steady-state numerical analyses by finite element method with some elasto-plastic models. In these analyses, however, there is no consideration about the time-dependent state that might bring non-negligible errors between measured and estimated results of the behavior.

This paper presents a progressed analysis method that simultaneously considers the processes of seepage and deformation of dam embankment, and shows the result of the analysis during the first impoundment of reservoir about a rock fill dam in Japan, named Kodamata Dam.

The result of the analysis is considered to have been able to express qualitative behavior based on condition change of unsaturated soil. However, there is no good coincidence from viewpoint of quantity so as that the surveyed value under impoundment of dam is smaller than the analyzed result. This main reason is considered due to an affect of condition for analysis parameter, and so future studies on the base of improvement of accuracy with abundant data will be able to obtain a result of analysis that will accord quantitatively as well as qualitatively.

This model is able to analyze continuously the behavior of dam embankment by an analysis, and it will practically be a useful method with improvement of analysis conditions including analysis parameters.

INTRODUCTION

In order to obtain substantial information for maintenance of dams, studies focusing future behavior of dam embankment have been carried out before the commencement of the first impoundment of reservoir. Up to now the predict of dam-behavior is mostly depending on studies which analyze individual behavior-predicts about deformation and seepage separately as follows:

Table-1 Present analysis method on behavior of embankment dam

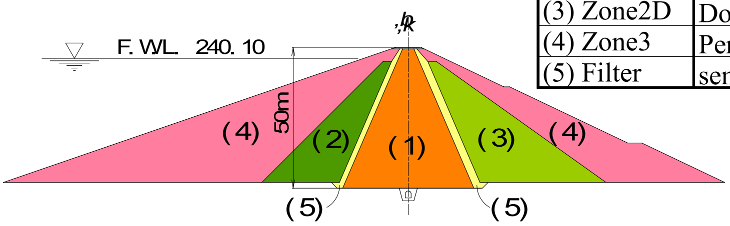
Behavior predict of displacement	elastic stress analysis by finite element method load of reservoir water is hydrostatic pressure on impervious surface
Behavior predict of permeability	steady permeable flow analysis by finite element method analysis domain is limited to saturated zone

In this method, the analyzed result of embankment behavior dose not hold good accordance accord with the surveyed one, because it does not reflect the state change of embankment condition (domain change from elastic to plastic, and from saturated to unsaturated.)

This paper has described a behavior predict at impoundment of reservoir by soil-water coupled analysis with finite element method (FEM) using elasto-plastic model which takes consideration of above change of embankment characteristic during impoundment work.

OUTLINE OF EMBANKMENT DAM

The concerned dam,Kodamata Dam, is 50m high rock and earth embankment type with central impervious core. The dam consists of impervious zone (Zone 1 center), and filter, semi-pervious zone (Zone 2) and pervious zone (Zone 3) to outside. Fig-1 and Table-2 show a standard section of dam and content of dam.



(1) Zone1	Impervious zone(k = 3.4Ч10^{-6}cm/s)
(2) Zone2U	Upstream semipervious zone(k = 9.4Ч10^{-4}cm/s)
(3) Zone2D	Downstream semipervious zone(k = 3.1Ч10^{-4}cm/s)
(4) Zone3	Perious zone(k = 5.5Ч10^{0}cm/s)
(5) Filter	semipervious zone(k = 2.8Ч10^{-2}cm/s)

Numerical value in a parenthesis shows the mean of permeability coefficient

Fig-1 The standard section of dam

Table-2 The content of dam

Dam type	Central impervious zone type
Dam height	50.0m
Available depth	28.1m
Lengh of dam crest	347.0m
Width of dam crest	9.0m
Dam volume	801,000m^3

The foundation of dam consists of pumice tuff (Yt1) and volcanic conglomerate (Vcl) which are distributed at present riverbed, and tuff breccia (Tb) which forms upper layer in the abutment and lower layer in the whole foundation. Table-3 shows hardness and permeability of each geological classification. Tuff breccia (Tb) has somewhat wide range of elasticity and permeability coefficient as shown in Table -3. It is, however, possible to make Tuff as a grouping because of its sedimentary environment or rock countenance such as matrix and containing gravel and sand contents.

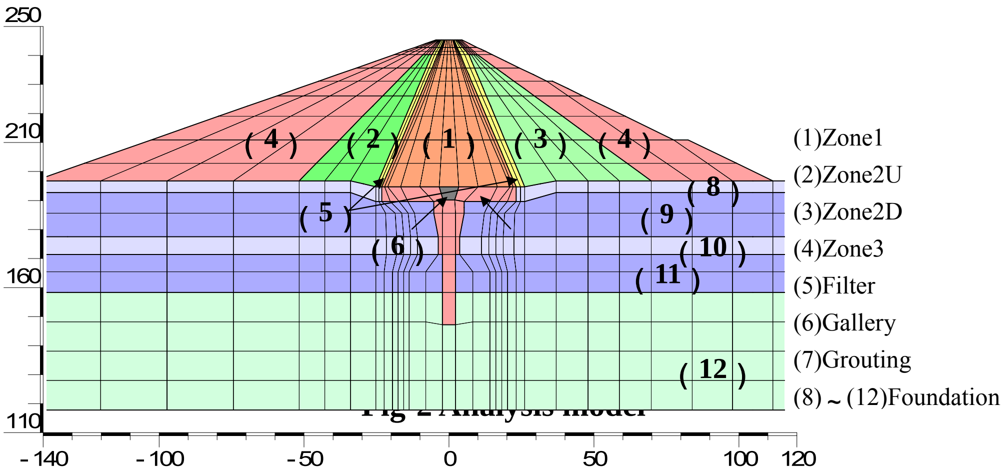
Table-3 Elasticity and permeability each geological classification

Geology classification	Elasticity coefficient (kN/m^2)	Permeability coefficient (cm/s)
Tuff breccia(Tuff)	119900 ~ 547400	$3.2\times10^{-5} \sim 1.6\times10^{-4}$
Pumice tuff(Yt1)	101900	2.3×10^{-5}
Volcanic conglomerate(Vc1)	219800	3.1×10^{-5}

ANALYSIS MODEL

The analysis model is simply applied two (2) dimensional model. Three (3) dimensional model is considered not to be necessary because rock formation of dam foundation is mostly level and both of left and abutment banks have even slopes along river course. Fig-2 shows an analysis model.

As a boundary condition for the analysis, the ground water level before reservoir filling is defined to accord with ground surface of dam site. In impounding process of reservoir hydrostatic head acting at foundation surface and rock zone at upstream side corresponds to a reservoir head. The bottom end of foundation for analysis extent, where it defined to be rigidly impervious and hard, is given 1.5 times thickness of equivalent dam-height.



ANALYSIS PARAMETER

The analysis parameter is mainly classified into following 5 kinds, Elasticity, Plasticity, Soil water retention, State surface, Permeability (Kohgo.et.al.2002a). There briefly shows how to decide these parameters as follows.

Elasticity Parameter

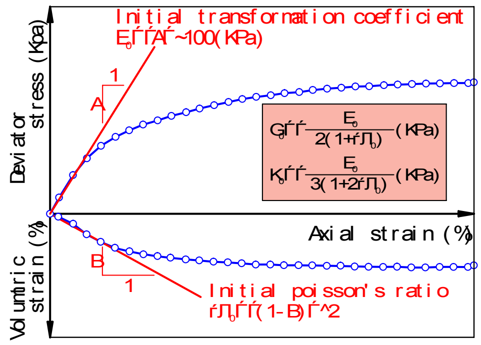
In elastic field, the shear modulus (G) and the bulk modulus (K) are defined as to be the following formula as a function of a mean effective stress and the second invariable J2 of deviatoric stress (at the state of tri-axial stress situation, it is expressed as lower easy formula.)

$$G = G_i + \gamma_j \times \sqrt{J_2} - \gamma_p \times P' \quad (1) \qquad K = K_i + \frac{-2.3 \times (1 + e_0)}{\kappa} \times P' \quad (2) \qquad ※J_2 = \frac{(\sigma_1' - \sigma_3')^2}{3}$$

Gi, γj, γp, Ki, κ, e0 are material parameters and are obtained through results of tri-axial compression test, consolidation test and field density test.

Parameter Gi and Ki are calculated as following: Fig-3 to Fig-5 is arranged through tri-axial compression test. At first, as Fig-3, G0 and K0 are calculated under confining pressure condition. As shown in Fig-4 and Fig-5, Gi and Ki are calculated with the relation between G0 and K0, and restrict pressure (p').

Parameter γ_j and γ_p are calculated as to substitute α* and K* that are arranged through tri-axial compression test.



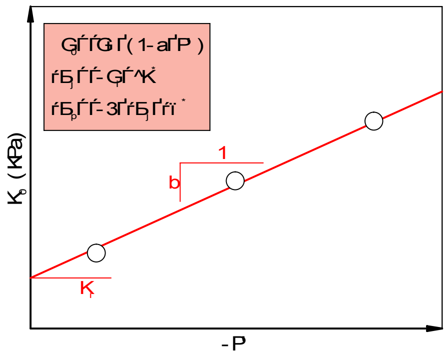
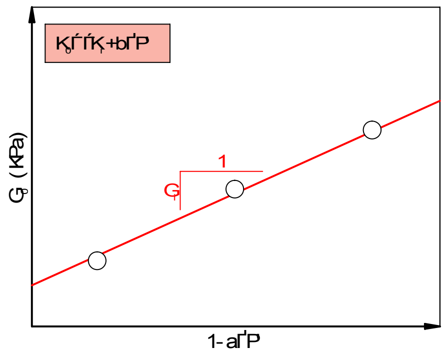


Fig-3 Tri-axial compression test result **Fig-5 K_0-p' relationships**



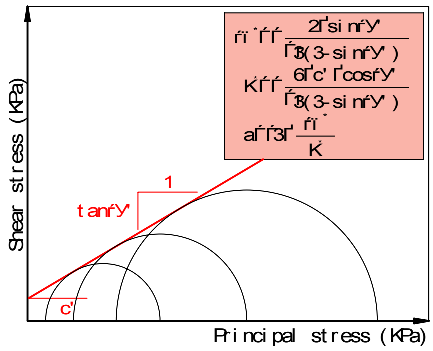


Fig-4 G_0-(1-ap') relationships **Fig-6 Mohr's stress circle**

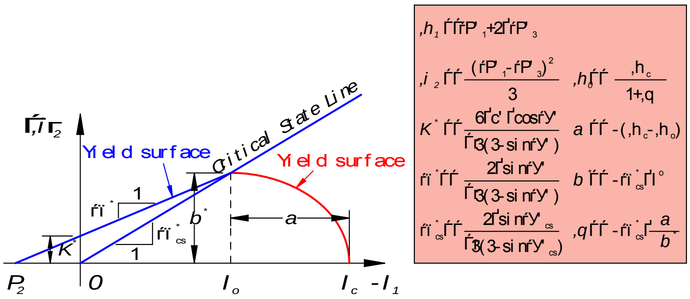
Parameter κ is an incline in elastic field through arrangement of e-log P' curve based on result of consolidation test. Parameter e0 is an initial condition of void ratio and is the mean value of field density test.

Plasticity Parameter

The regular yield face for this elasto-plastic model is one to put ellipse cap on a failure face of Mohr-Coulomb type. The projection to 2nd dimensional section is as Fig-7.

As for analysis parameters, there are internal friction angle φ' in Mohr-Coulomb's failure criterion, internal friction angle φ'cs in critical state line, aspect ratio R of ellipse cap, and consolidation yield stress Ic. K*, a, b*, I0, α*, α*cs shown in Fig-7, are defined as Fig-7 through 4 parameters (φ', φ'cs, R, Ic).

Parameter φ' is arranged from a slope of covering line of critical circle at shear failure (Refer to Fig-6). Parameter φ'cs is calculated with stress paths based on a result of tri-axial compression test, critical state line of the steepest in strait lines to connect plot and original point in the map (Refer to Fig-8).



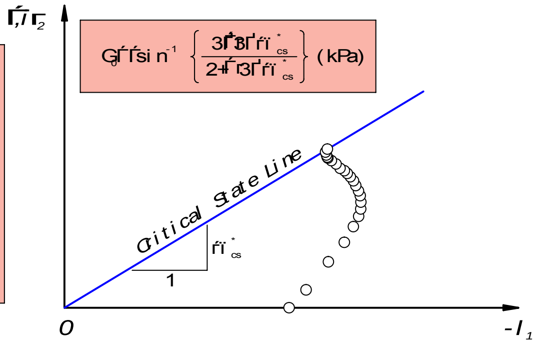


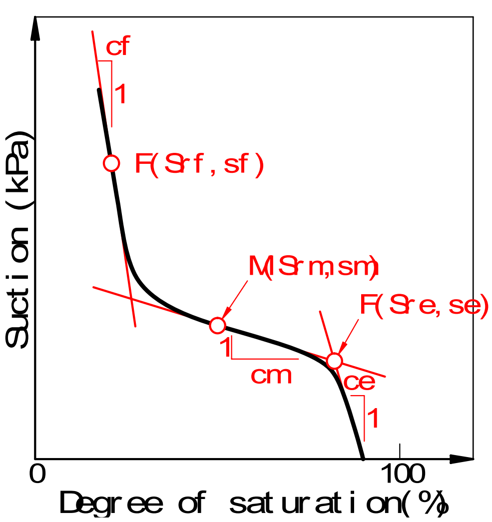
Fig-7 Yield surfaces of the elasto-plastic model **Fig-8 Stress paths**

Parameter R is R=1.0 which is adapted in a case of isotropy state line. The consolidation yield stress Ic will be mentioned together with later-mentioned state surface parameter.

Soil Water Retention Parameter

In this analysis it is put into consideration to two suction effects shown at next in order to reenact dynamics behavior of unsaturated geo-materials.(Kohgo, et al, 2002b, 2005) Those are (1) increase of effective stress due to increase of suction, and (2) increase of yield stress due to increase of suction and change of stiffness against plastic deformation.

The suction increases or decreases dependant upon moisture amount in soil and this relation is shown as the soil water retention curve. Fig-9 is a soil water retention curve which is expressed by a tangential model (Hayashida et al, 2003), that is used for this analysis.



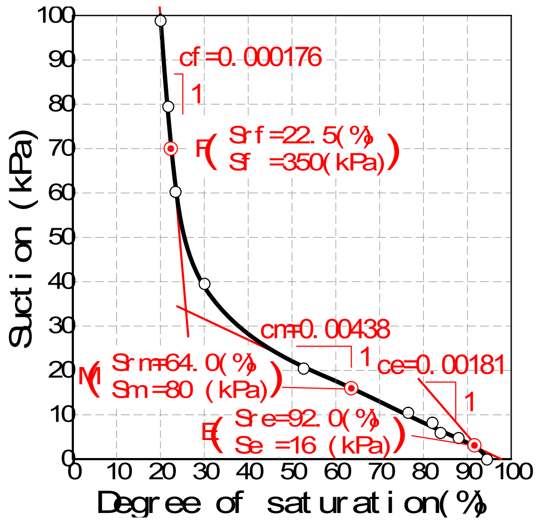


Fig-9 Soil water retention curve (Tangential model)

Fig-10 Soil water retention curve (Zone2U)

For the calculation of parameters about Zone 2U (semi-pervious zone at upstream) soil material variation extent of saturation will be large during impoundment of water, and so moisture maintenance test is applied to obtain data for parameters. Fig-10 shows result of moisture maintenance test and analysis parameter on Zone 2U. Other parameters are from values generally used.

In addition, two above mentioned suction effects are given as a function of effective suction s*. s* is defined as following formulas.

$s^*=s-se(s>se)$ (3)

$s^*=0(s<se)$ (4)

Where, s: amount of suction under optional condition on saturation ratio

se: amount of suction at air intrusion

Namely, when saturation ratio is Sr≧Sre (saturation ratio at air intrusion), there is no suction effect. In a case of Sr≧Sre it seems in appearance as “unsaturated” due to the moisture among soil particle includes air bubble, and so the gap among soil particle is mostly filled with water and the capillary pressure does not work as to form meniscus

State Surface Parameter

Here mentioned state surfaces shows the relation of voids ratio and mean effective stress P’ in plastic field (normal consolidation field). The state surface of saturated geo-material is shown in Fig-11 and it coincides with normal consolidation line to be defined by Γ (voids ratio) and λ (slope of straight line).

On unsaturated geo-material, the state surface varies with amount of suction (or saturation ratio of geo-material). Γ is replaced to Γ* and λ is replaced to λ*. (refer to Fig-11.) Γ* and λ* define this state surface of unsaturated one are calculated by following formulas.

$$\lambda^* = \lambda + \frac{\lambda f^* \times s^*}{s^* + a^*} \quad (5) \qquad \Gamma^* = e_0^0 + \frac{(\Gamma - e_0^0) \times \lambda^*}{\lambda} \quad (6)$$

λf*, a* and e00 are material parameters and on Zone 2U (semi-pervious zone at upstream) they are obtained with consolidation test changing initial saturation ratio. Other parameters except Zone 2U are form values generally used. The followings are explanation on calculation of analysis parameter.

At first, it is to make equi-degree curve e-log P’, shown in Fig-11 through consolidation test changing initial saturation ratio. To extend plastic field (each state surface) forward left-upper direction, a face meets an intersection point. The voids ratio of point is e00.

At next, there are arranged the slope λ* of e-log P’ curve (plastic field) each degree of saturation and effective suction s* (Tangential Model) corresponding to initial saturation ratio at consolidation test. From them, related figures are shown in Fig-12. λf* is calculated from slope on approximated straight line of the above and a* is calculated from its interception.

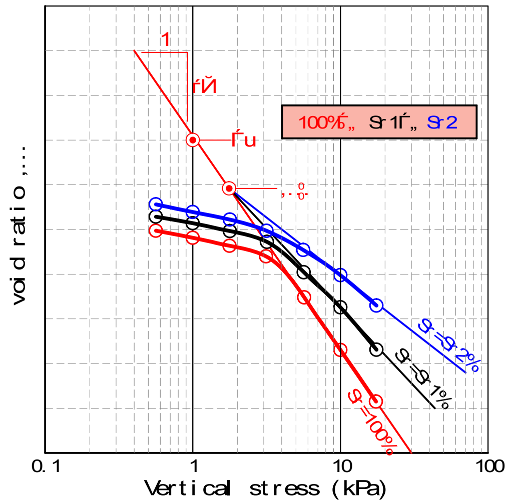


Fig-11 Concept of state surface

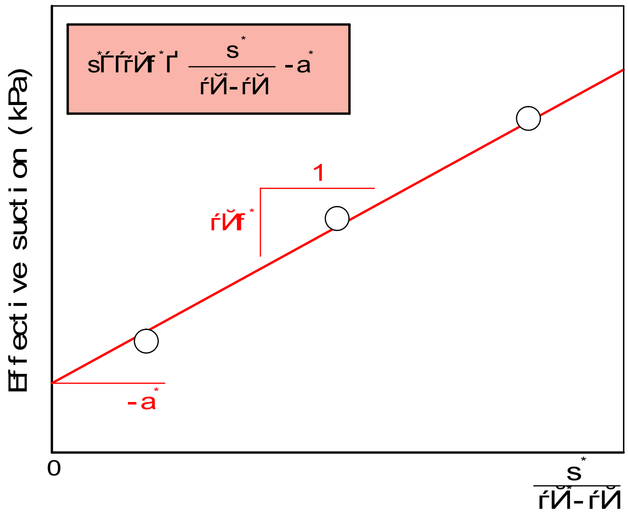


Fig-12 s*- $\dfrac{s^*}{\lambda^*-\lambda}$ relationships

Though the consolidation yield stress Ic is primarily included in plasticity parameter, it has also relation with state surface and so it is described in this section.

Ic is effective stress value at intersection point of both state surfaces of elastic and plastic field at stage of soon after embankment. (It is an initial value of yield stress before stress history of embankment load and impoundment process.) The definition of elastic and plastic fields is as follows.

Elastic field : pass through state of immediate after embankment and is straight line with slope κ

At soon after embankment, only U_{eq} (equivalent pore pressure by suction) is assumed to act as load.

Plastic field : state surface to correspond to effective suction at stage of soon after embankment is calculated by formula (5) and (6).

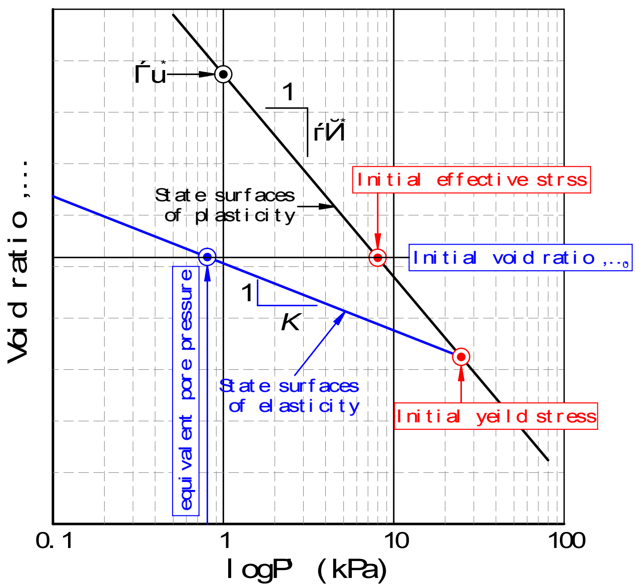


Fig-13 Concept of initial yield stress Ic

Permeability Coefficient

Permeability coefficients dam and foundation are basically determined based on result of field permeability test for embankment, result of lugeon test at pilot hole for dam foundation and target value of improving work for grouting part of foundation, respectively.

List of Analysis Parameters

Table-4 is list of parameters, which are shown in this following section. However, those related to foundation ground are omitted from this list as they are handled in elastic condition only.

Table-4 Material parameters for Analysis

	Initial condition				Elasticity					Plasticity			
	Sr_0	s_0 (kpa)	e_0	γ (kN/m^3)	G_i (kpa)	γ_j	γ_p	K_i (kpa)	κ	φ'	φ'_{cs}	R	Ic (kN/m^2)
Zone1	0.914	32.0	0.77	18.9	2000	-39.1	31.7	10300	0.050	34.6	37.8	1.0	152
Zone2U	0.790	45.7	0.47	20.3	3200	-70.0	62.7	83200	0.027	38.0	40.3	1.0	233
Zone2D	0.790	45.7	0.47	19.4	2600	-65.1	51.7	43400	0.027	33.9	36.5	1.0	233
Zone3	0.172	0.3	0.30	20.5	10900	-92.0	95.4	80700	0.039	43.7	47.1	1.0	149250
Filter	0.363	0.3	0.23	21.8	3000	-57.2	57.2	51800	0.037	42.2	43.5	1.0	464159

	State surface					Permeability & soil water retention									
	λ	Γ	e^0_0	λf^*	a^*	k (cm/s)	s_e (kpa)	Sr_e	s_m (kpa)	Sr_m	s_f (kpa)	Sr_f	c_e (1/kpa)	c_m (1/kpa)	c_f (1/kpa)
Zone1	0.138	1.032	0.000	0.000	1.00	3.4×10^{-6}	40.0	0.900	80.0	0.640	350.0	0.230	-	4.4×10^{-3}	1.8×10^{-4}
Zone2U	0.168	0.824	0.569	0.092	85.56	9.4×10^{-4}	16.0	0.920	80.0	0.640	350.0	0.225	1.8×10^{-3}	4.4×10^{-3}	1.8×10^{-4}
Zone2D	0.168	0.824	0.569	0.092	85.56	3.1×10^{-4}	16.0	0.920	80.0	0.640	350.0	0.225	1.8×10^{-3}	4.4×10^{-3}	1.8×10^{-4}
Zone3	0.154	0.856	0.055	0.085	0.12	1.0×10^{-3}	0.1	0.850	0.2	0.500	0.9	0.100	-	2.5×10^{0}	8.3×10^{-2}
Filter	0.154	0.856	0.055	0.085	0.12	1.0×10^{-3}	0.1	0.850	0.2	0.500	0.9	0.100	-	2.5×10^{0}	8.3×10^{-2}

RESERVOIR FILLING CURVE

The impounding pattern of reservoir is made based on simulation by using discharge data of past 10 years at dam site. And the fifth water-sufficiency year during 10 years is applied for impounding pattern. (Fig-14, blue line)

The impounding starts at 200 m of water level. Then it reaches 240 m of the high water level by raising 40 m in 5.5 months, keeps high water level for one (1) month, and descends 30 m through one month.

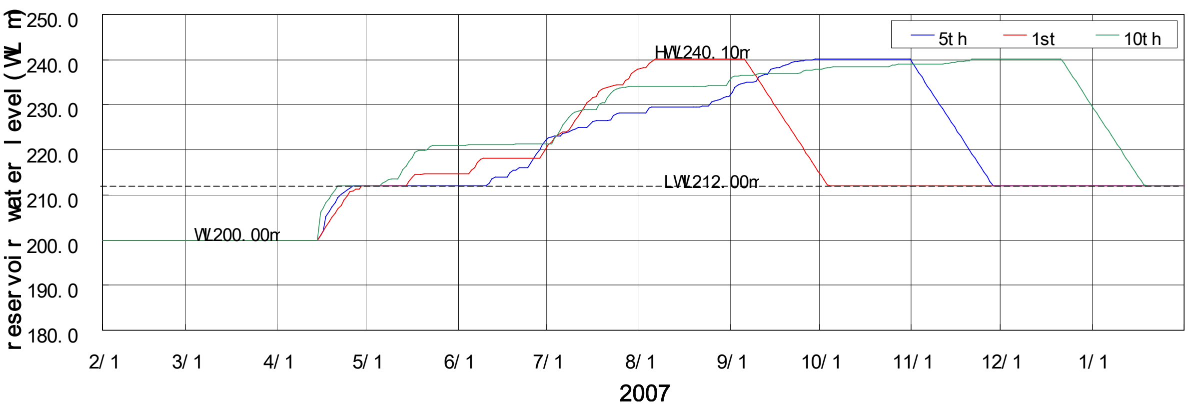


Fig-14

ELASTO-PLASTIC ANALYSIS

Based on former mentioned conditions, there implemented an analysis for the behavior of rock-fill dam during the first impoundment of reservoir by using an elasto-plastic model. The result of analysis is summarized including comparison with result of impoundment as follows.

Fig-15 shows a displacement at dam from embankment stage to impounding stage. (In advance of the analysis during impoundment of reservoir, a static stress and deformation analysis of dam embankment is performed to obtain initial condition for the analysis by FEM.

During embankment process, the settlement amount of dam body increases with progress of embankment. The big settlement amounts are calculated in Zone 1, Zone 2U and Zone 2D, which have small elastic coefficients with small initial yield stress, and in lower part of each Zone plastic deformation is analyized after elastic deformation. The maximum settlement at embankment stage occurred in Zone 1, where its analysis result of 73.9 cm is approximately accorded with actual measurement of 66.0 cm .

During impounding process of reservoir , the result of analysis shows the tendency that each zone of dam has horizontal displacement somewhat to downstream-ward with ascent of reservoir water level and rebounds to upstream-ward with descent of water level. For vertical direction, the displacement is upward with ascent of water level and downward with descent of water level. The portions of dam body with big displacement are at dam crest and it’s around upstream slope.

Fig-16 shows a relation between horizontal and/or vertical displacement at dam crest (black dots at Fig-15.) and reservoir water level. Referring to the Figures, the displacement amount at descent of reservoir water level is bigger than at ascent. This reason is considered to be an affect of state variation of embankment (unsaturated to saturated) in Zone 2U.

Table-5 State variation of Zone 2U on impounding process of reservoir

Ascent of reservoir water level	Variation from unsaturated to saturated condition by impoundment of water. Distinctive decrease of effective stress (expansive displacement) and saturated collapse simultaneously appeared.
Descent of reservoir water level	With water release, increase of effective stress and affect of saturated collapse at ascent of reservoir water level simultaneously appeared that caused bigger compression displacement.

In these figures displacements by the result of analysis and actual record at impoundment of reservoir are shown. Comparing both displacements, actual record is smaller than result of analysis on both horizontal and vertical displacements.

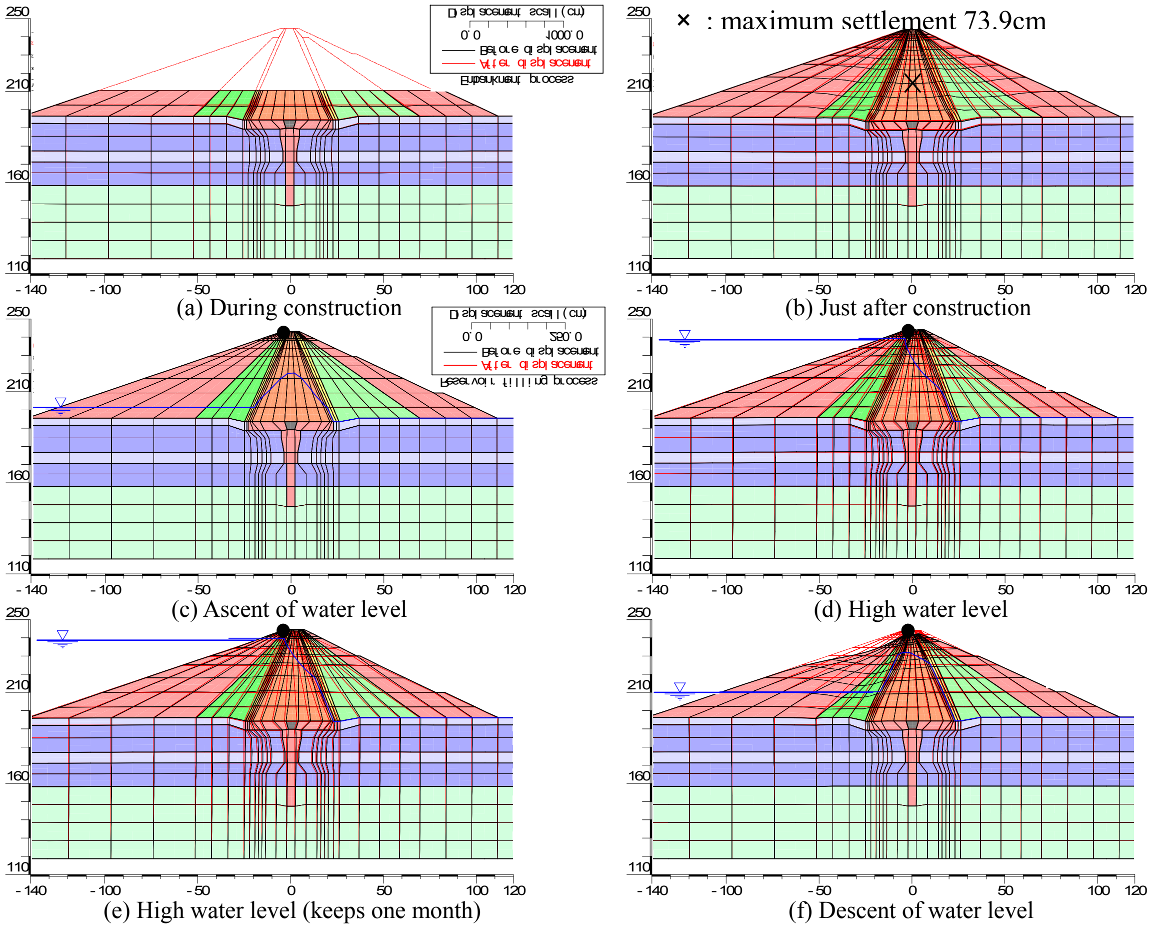


Fig-15 Displacement at embankment and reservoir water level

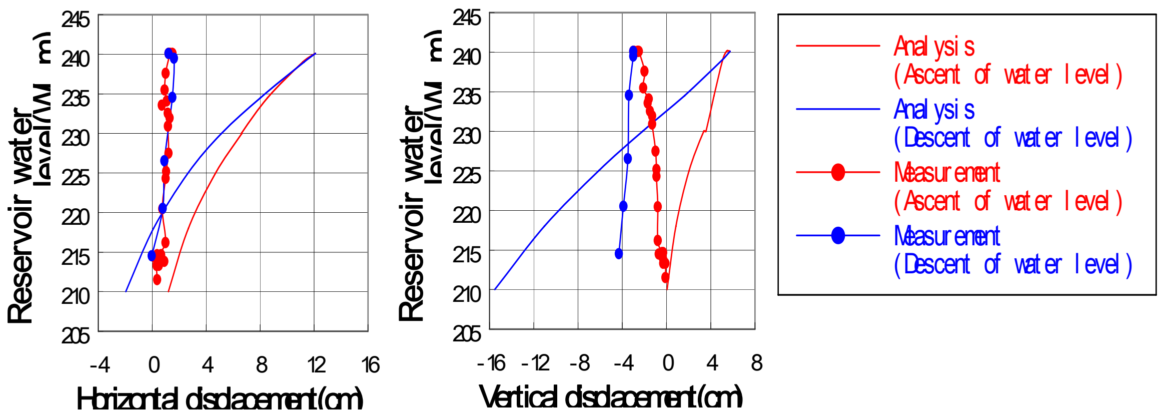


Fig-16 Horizontal and Vertical displacement of dam crest

Fig-17 shows distribution of maximum principal stress at impounding reservoir. At ascending time of reservoir water level, the maximum principal stress on upstream of Zone 1 decreases due to expansion of saturated domain (increase of pore water pressure). The domain of big stress concentrates around basement at Zone 1 downstream. On the contrary, the maximum principal stress during descent of reservoir water level increases at upstream domain of Zone

1 because of decreasing pore water pressure. At the completion of impoundment there remains pore water pressure in Zone 1 (see Fig-18). The effective stress at upstream of Zone1 remains smaller than that of starting stage of impoundment.

The principal effective stress in filter zone has been mostly constant without so much variation through whole impounding process, though it had trend to have concentration of stress inside at starting stage of impoundment.

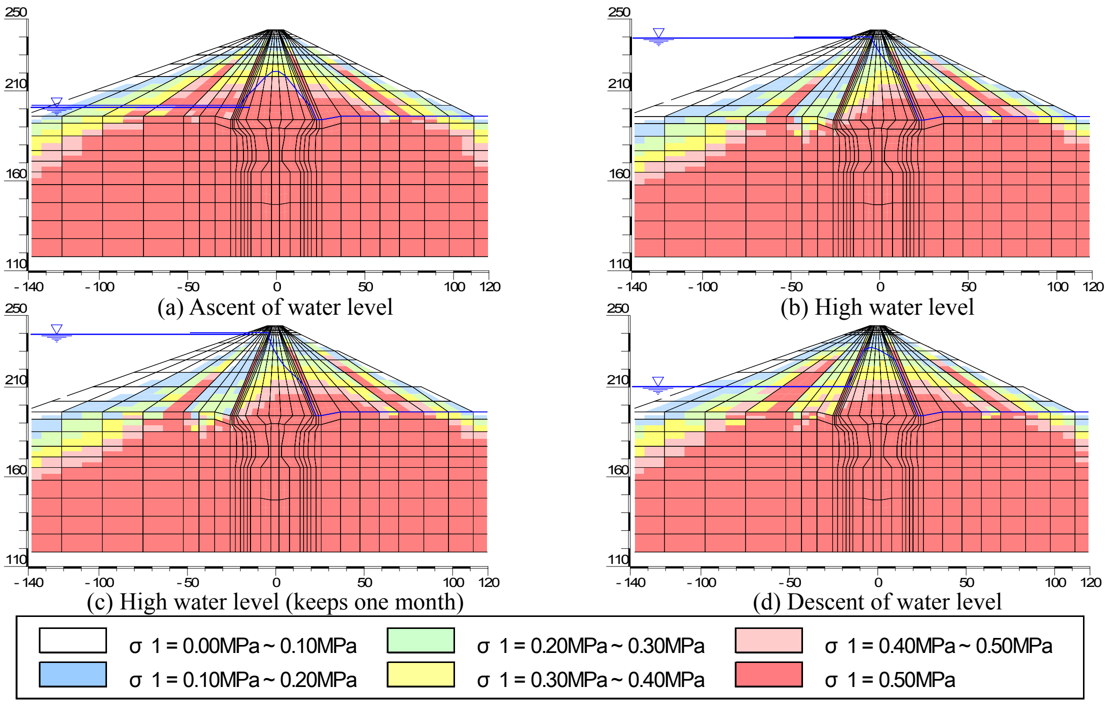


Fig-17 Distribution of maximum principal stress at reservoir filling

Fig-18 shows a chart of velocity vector. (Blue line in a chart shows equi-potential line.) According to the chart, the pore water pressure occurred on embankment process remains at starting stage of impoundment. With ascent of reservoir water level, the saturated domain is expanded.

The saturated domain is gradually expanded with maintaining high water level and the state line shifts from unsteady to steady state.

At descent stage of water level, the decreasing of water pressure in Zone 1 is small as descent speed is fast.

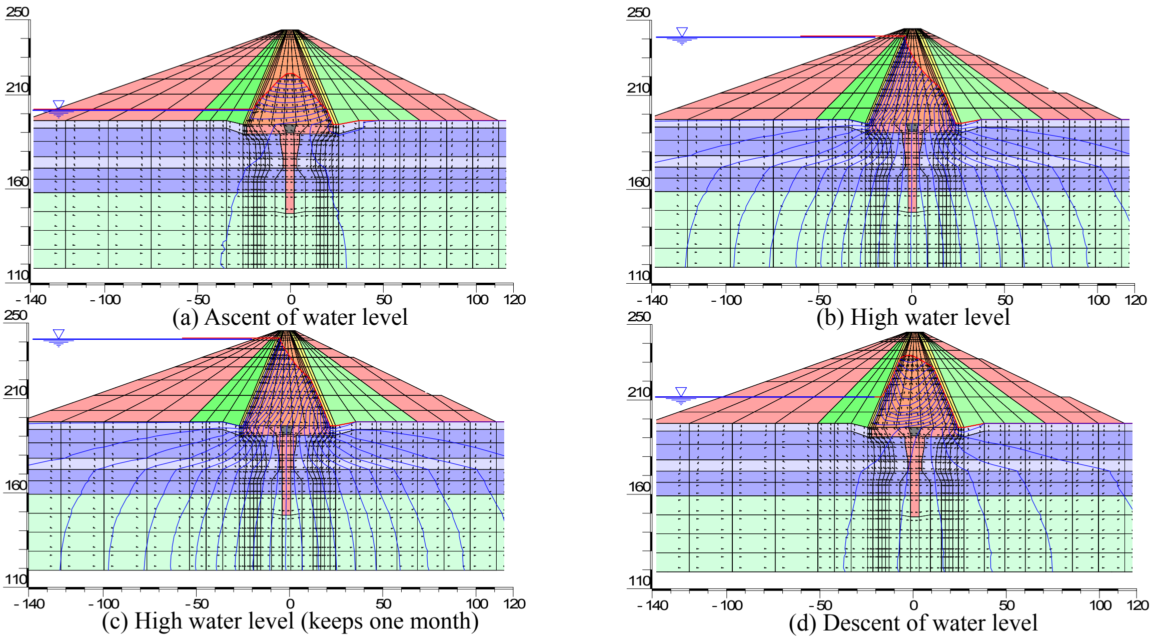


Fig-18 Vector Chart of Flow Velocity

CONCLUSION

For the first impoundment of reservoir the soil-water coupled analysis using an elasto-plastic model with consideration of state variation for unsaturated geo-materials. The result of analysis is judged as to be able to represent qualitative behavior of dam embankment caused by seepage of reservoir water. However, the result of analysis compared with actual measurement of deformation and displacement under impoundment of reservoir was smaller than result of analysis and so it did not quantitatively coordinate to the actual one. The main reason is considered to be an affect due to parameter of analysis which could not derived sufficient data for various testing conditions presently. With abundant data of soil testing it will be able to obtain good result of analysis to coordinate quantitatively..

Finally, this model judged to be useful method for practical works with the improvement of accuracy of analysis conditions including parameters of analysis, because it can continuously and simultaneously analyze behavior of dam embankment with handling both aspects of stress distribution and seepage flow.

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