LONG-TERM DEFORMATION USED AS INDICATOR REPRESENTATIVE OF HIGHWAY EMBANKMENT ON SOFT FOUNDATION

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ABSTRACT

For the highway embankments on soft foundation, excessive long-term settlement and deformation are usually seen as a result of consolidation settlement. The authors consider that settlement and deformation of highway embankments are the indicators effectively applicable to road asset management. A set of indicators describing the long-term deformation of the deteriorating fill body may be a sort of promising indicators to predict the change in pavement functionality and degree of pavement damage in the future.
In this paper, discussed are the indicators representative of highway embankments on soft foundation and the applicability of soil-water coupled finite element analysis as a tool for supporting road asset management. The analysis was conducted in analyzing the 20 years old existing highway embankment and its predictability of settlement and deformation during and after construction was verified. This analysis could successfully simulate the long-term stress deformation behavior of the actual road embankment resulting in the analyzed performance of the embankment in accordance with the performance monitored at the site. Based on the results of the simulation, the life-cycle cost analysis of the highway embankment on soft foundation was conducted and compared with cost actually needed in the past 20 years.

1. INTRODUCTION

Excessive long-term settlement and deformation of highway embankment on soft foundation are usually seen as a result of consolidation settlement and affects the functionality of pavement and other road facilities. The authors consider that a set of indicators describing the long-term deformation of the deteriorating fill body may be a sort of promising indicators effectively applicable to planning of maintaining, upgrading, and operating road assets.

In this paper, the soil-water coupled finite element analysis was conducted in one of the post mortem analysis of the highway embankment of the Hokkaido Expressway to verify its predictability of long-term settlement and deformation as a tool for supporting road asset management. In the analysis, the constitutive model employed was an elasto-visco-plastic model proposed by Sekiguchi and Ohta in 1977. The soil parameters were estimated based on laboratory and field tests together with a set of correlations proposed by many research workers.

The life-cycle cost estimated based on the analyzed settlement and deformation was compared with the life-cycle cost actually needed in the past 20 years. In this life-cycle cost analysis, the road vertical alignment and the faulting between a bridge abutment and adjacent pavement were investigated as the performance-related indicators relevant to settlement and deformation of highway embankment on soft foundation. Based on these indicators, the life cycle of pavement on the highway embankment was investigated and then the life-cycle cost estimation was implemented.

In this paper, discussed are the indicator representative of highway embankments on soft foundation and the applicability of soil / water coupled finite element analysis as a tool for supporting road asset management.

2. ASSET MANAGEMENT FOR HIGHWAY EMBANKMENT ON SOFT FOUNDATION

In road asset management, the short and long-range planning of maintaining, upgrading, and operating road assets are drawn up on the basis of performance models of each road facilities. It is indispensable for these performance models to consider the long-term settlement and deformation that have great influence on the road deterioration in highway embankment on soft foundation.

The proposed asset management sub-system for highway embankment on soft foundation is shown in Figure 1. The concept of this sub-system is the application of soil-water coupled finite element analysis as a tool for performance prediction of highway embankment on soft foundation.

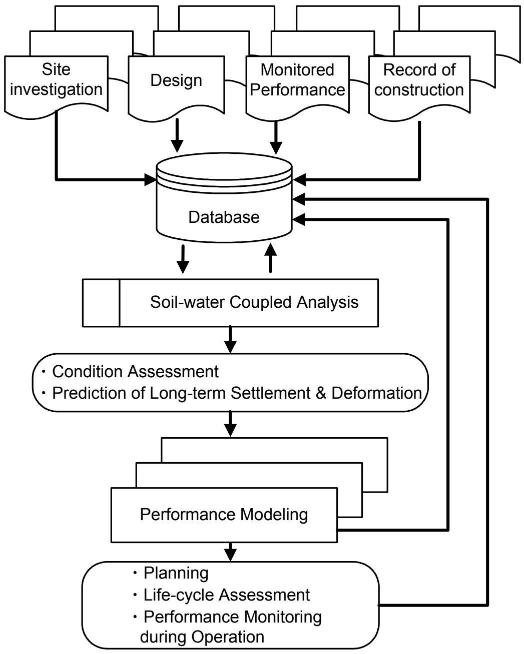


Figure 1 - Proposed asset management sub-system for highway embankment

The database is that of a collection of laboratory and field data of subsoil, information of design, records of construction and monitored performance during construction. Based on these data, the soil-water coupled finite element analysis can be conducted in one of the post mortem analysis during the embankment construction. The constitutive equation and soil parameters can be selected or modified after trial fitting with monitored performance during construction. It is considered that these calibrations are one of the condition assessments of highway embankment on soft foundation for uncertainty of ground information in design.

The authors assume that the analysis may successfully predict the long-term settlement and deformation of the highway embankment during operation by extending the boundary conditions to longer time period if the analysis can successfully simulate the deformation behavior during construction. Based on this prediction, the performance modeling of each road facilities can be carried out. The data of performance monitoring during operation is feed back to the database as well as the results of analysis. Utilizing the database, improvement of performance models, development of alternatives can be done by repeating the analysis from time to time. It is considered that the asset management sub-system supported by the soil - water coupled finite element analysis bring about effective decision makings using readily available quantitative and qualitative information on the basis of advanced geotechnical engineering.

3. PREDICTABILITY OF LONG-TERM SETTLEMENT AND DEFORMATION BY SOIL-WATER COUPLED FINITE ELEMENT ANALYSIS

3.1. Analyzed site and subsoil properties

The Hokkaido Expressway between Sapporo and Iwamizawa in Hokkaido, the north district of Japan was constructed from 1980 to 1982 and opened to traffic in 1983. Out of the length of 32km connecting Sapporo to Iwamizawa, a length of 17km was designed as a 6-8m high embankment on a plane covered with very soft peat and clays. Long-term settlement and deformation of embankment had occurred in the past 20 years. The area covered with highly compressive peat layer of 1-5 m thickness on alternation of soft clay layers and sand layers of 20-30 m thickness. Subsoil properties of this area are extremely poor.

The sections analyzed in this paper are shown in Figure 2. These were placed 20km away from Sapporo. The analyzed sections are Ebetsu Trial Embankment and the actual highway embankment work at Ebetsu-Futo East Works that located near the Ebetsu Trial Embankments. The Echigo swamp is located on north side in this section was partly reclaimed. The very soft peat layer with 500 to 1000% of natural water content had deposited this part on the surface by a thickness of 4 to 5m.

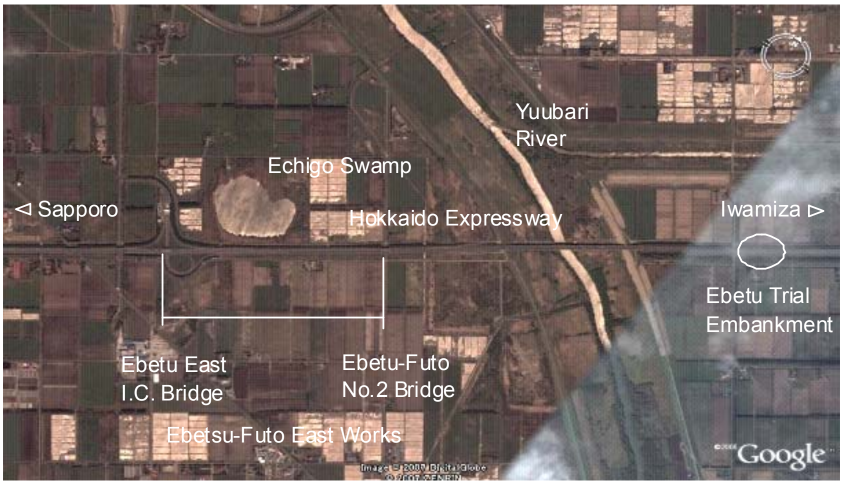


Figure 2 - The analyzed section in Hokkaido Expressway (©Google)

3.1.1 *Ebetsu Trial Embankment*

Ebetsu Trial Embankment started to construct in 1977 aiming at collecting the data needed in designing the highway embankment from Sapporo to Iwamzawa. The trial embankment consisted of Non-treated test fill and Sand drain-treated test fill sections. Cross sections and subsoil profiles of these trial embankments are shown in Figure 3 and Figure 4. In Sand drain-treated test fill, 10m length and 0.4m diameter sand drains were installed in triangle pattern in plan with a 1.8m center to center pitch to accelerate the consolidation of peat and clay layers.

The 1m thick sand mat was placed on the ground surface to keep trafficability and drainability. Drain pipes of 0.1m diameter were placed from center to toe of the embankment inside the sand mat at every 4m interval along the longitudinal direction. Counterweight berms, pre-loading fill and extra fill were trialed. Slow banking method by staged loading were also performed with an observational construction method.

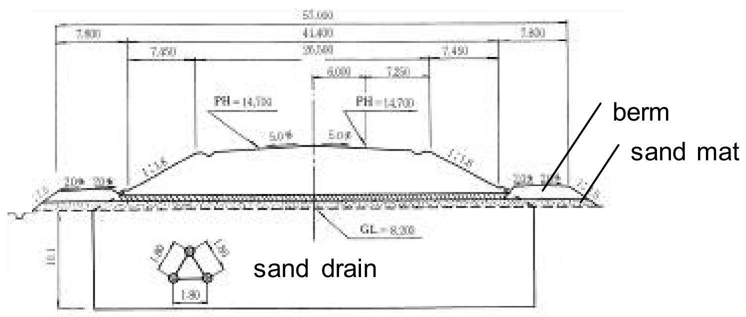
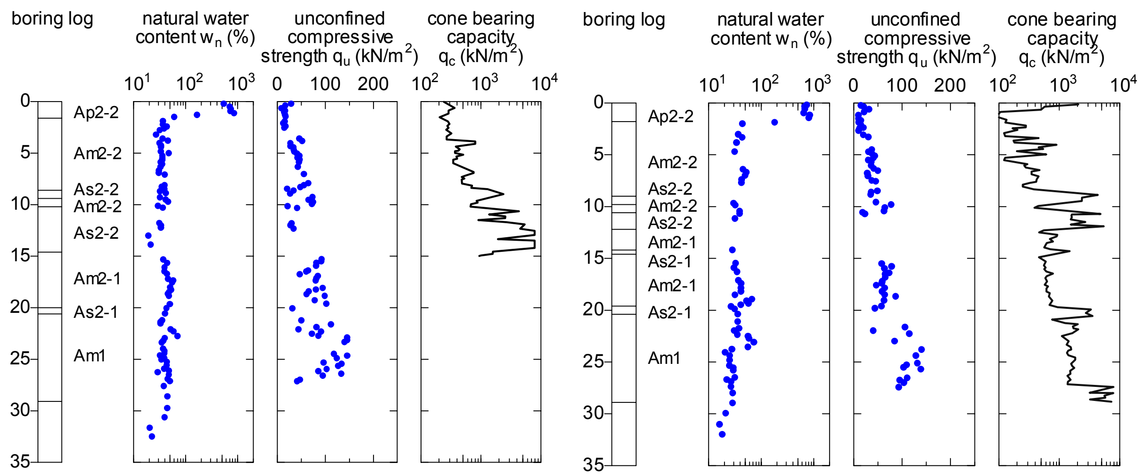


Figure 3 - Cross section of Ebetsu Trial Embankment (Sand drain-treated fill)



(a) Non-treated test fill

(b) Sand drain-treated test fill

Figure 4 - Subsoil profiles of Ebetsu Trial Embankments

3.1.2 *Ebetsu East Works*

Ebetsu-Futo East Works were performed from 1980 to 1982. Length of the analyzed section is 1025 m from Ebetu East I.C. Bridge to Ebetu-Futo No.2 Bridge. The analyzed cross sections of the actual embankment work are classified into four sections. The typical cross section of the embankment is shown in Figure 5. Subsoil profiles of analyzed sections are shown in Figure 6. The peat layer is thick and natural water content is as high as that at Ebetsu Trial Embankment.

The sections of STA.162+40, STA.169+0 and STA172+20 were treated by sand drains which were installed in triangle pattern in plan with a 1.5-2.0m center to center pitch, 9-12m length and 0.4m diameter. The cross section of STA.165+40 was treated by sand compaction piles which were installed in square pattern in plan with a 1.4m center to center pitch, 10m length and 0.7m diameter.

The 1m thick sand mat was placed on the ground surface to keep trafficability and drainability. Drain pipes of 0.1m diameter were placed from center to toe of the embankment inside the sand mat at every 10m interval along the longitudinal direction. Berms, pre-loading fill, extra filling and surcharge by dewatering method were performed as countermeasures.

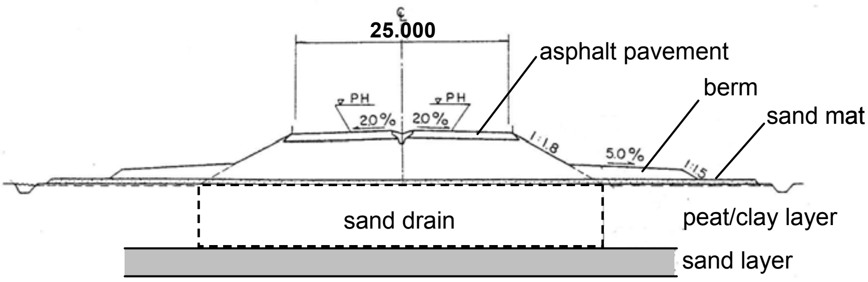


Figure 5- Typical cross section of the embankment in Ebetsu-Futo East Works

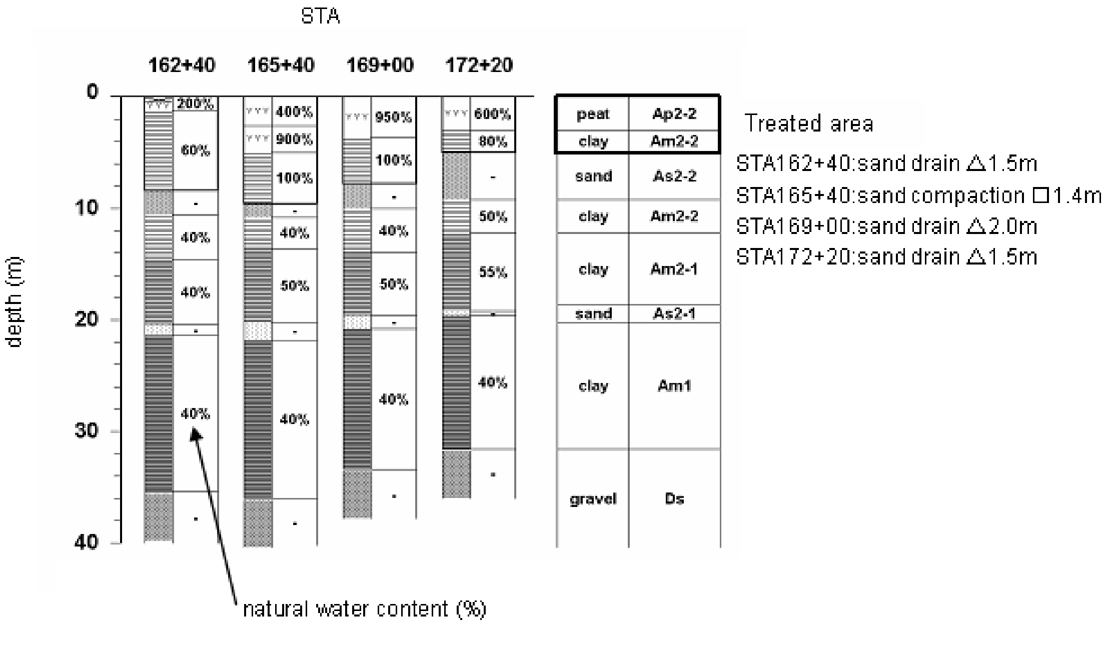


Figure 6 - Subsoil profiles of analyzed sections in Ebetsu-Futo East works

3.2. Finite element modeling and input parameter determination

The constitutive model mainly used in this analysis was an incremental elasto-viscoplastic model proposed by Sekiguchi and Ohta (1977) [1]. This model was developed based on a set of assumptions totally different from the original Cam-clay model by Roscoe, Schofield and Thurairajah (1963) [2] but the final mathematical form is founded to essentially the same as the original Cam-clay model. This model describes the inviscid characteristics of elasto-plastic soils as well as the time dependent characteristics of elasto-viscoplastic soils. In other words, the model describes the induced anisotropy, creep and relaxation characteristics of soils.

The soil-water coupled finite element code used in this analysis is DACSAR (Deformation Analysis Considering Stress Anisotropy and Reorientation) coded by Iizuka and Ohta (1987) [3]. Two-dimensional finite element modeling of Non-treated test fill in Ebetsu Trial Embankment is shown in Figure 7 as a typical finite element mesh formation. Modeling of the embankment is performed by adding elements to the mesh and loading rate and the thickness of the fill are assumed to be identical with those in the actual staged construction works. Furthermore the buoyancy to act under the fill body and drainage resistance of drain pipe are considered.

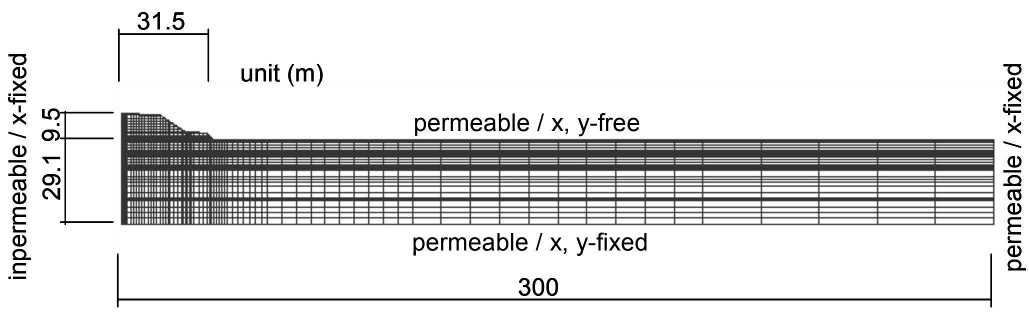
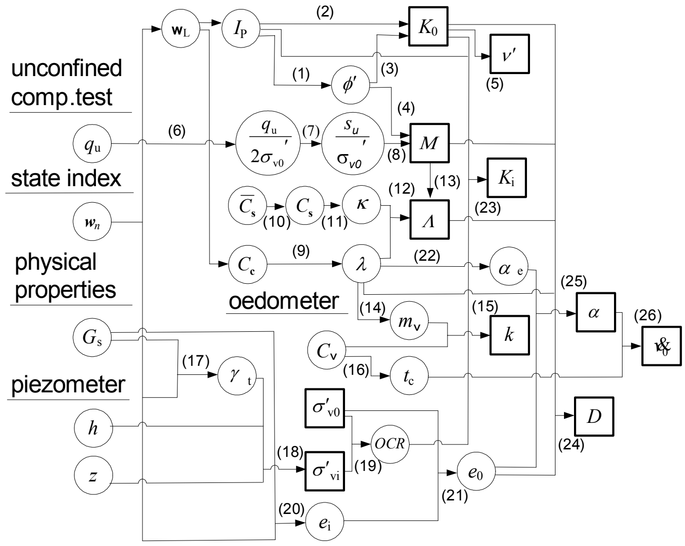


Figure 7 - Two-dimensional finite element mesh of the Non-treated test fill

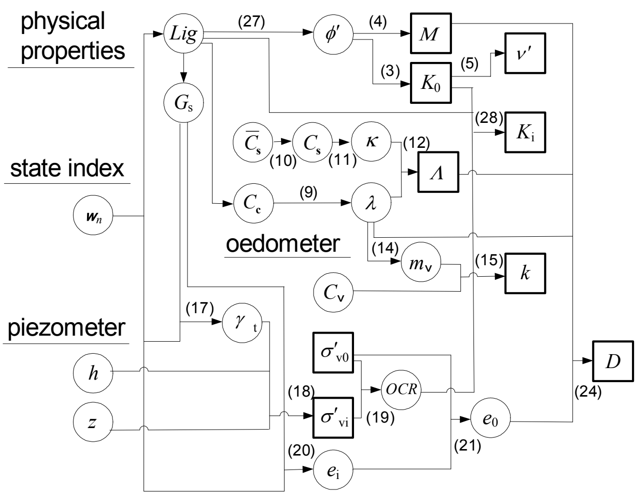
In this analysis, peat layer is assumed to be elasto-plastic. However, surface crust, shown in the result of cone penetration test (see Figure 4(b)), crust can have a significant influence on the result of settlement and deformation analysis. Therefore this crust is assumed to be linearly elastic. Clay layers are assumed to be elasto-visco-plastic. Compacted fill material, sand mat and sand layer are assumed to be linearly elastic.

The procedure of input parameter determination of clay and peat follow the charts shown in Figure 8 which is based on laboratory and field tests together with a set of correlations proposed by many research workers [3] [4]. Parameters needed in this model should primarily be determined through the triaxial test, oedometer test and permeability test. However these laboratory tests were not performed prior to these construction works. In this study, some local empirical correlations between natural water content and various soil properties are developed and the input parameters were determined using Figure 8 in which parameters in square are needed in the constitutive model.

The input parameters of surface crust and sand layer are determined by using correlation between the cone bearing capacity q_c and deformation parameters after Lunne and Christophersen (1983) [5] and Sanglerat (1972) [6].



(a) clay (elasto-visco-plastic model)



(b) peat (elasto-plastic model)

(1)	$\sin\phi' = 0.81-0.233\log I_p$	Kenny (1959)
(2)	$K_0 = 0.44+0.42\times10^{-2} I_p$	Massarsch (1979)
(3)	$K_0 = 1-\sin\phi'$	Jaky (1944)
(4)	$M = 6\sin\phi' / (3-\sin\phi')$	
(5)	$\nu' = K_0/(1+K_0)$	
(6)	$(q_u/2\sigma'_{v0})_{NC} = 1/(OCR)^{\wedge}(q_u/2\sigma'_{v0})_{OC}$	Ohta (1988)
(7)	$(S_u/\sigma'_{v0})_{CK_0UC} = \mu\,(q_u/2\sigma'_{v0})_{NC}$	Ohta (1988)
(8)	M determined using $(S_u/2\sigma'_{v0})_{CK_0UC}$	Ohta (1988)
(9)	$\lambda = 0.434\,C_c$	
(10)	$\overline{C_s} / C_s = 1-\log\beta/\log(OCR)$ $\beta = (1+2K_i)/(1+2K_0)$	
(11)	$\kappa = 0.434\,C_s$	
(12)	$\Lambda = 1-\kappa/\lambda$	
(13)	$\Lambda = M/1.75$	Karube (1975)
(14)	$m_v = 3\lambda/((1+e_0)(1+2K_0)\sigma'_{v0})$	
(15)	$k = m_v C_v \gamma_w$	
(16)	$t_c = H^2 T_v(90\%)/C_v$	Sekiguchi (1977)
(17)	$\gamma_t = G_s\gamma_w(1+\mathbf{w}_n)/(1+G_s\mathbf{w}_n)$	
(18)	$\sigma'_{vi} = \gamma_t z - p_w$	
(19)	$OCR = \sigma'_{v0}/\sigma'_{vi}$	
(20)	$e_i = G_s\mathbf{w}_n$	
(21)	$e_0 = e_i - \lambda(1-\Lambda)\ln(\overline{OCR})$ $\overline{OCR} = OCR\,(1+2K_0)/(1+2K_i)$	
(22)	$\alpha e/\lambda = 0.05\pm0.02$ (for clay) $\alpha e/\lambda = 0.07\pm0.02$ (for peat)	Mesri& Godlewshi (1977)
(23)	$K_i = K_0(OCR)^m$ $m = 0.54\exp(-I_p/122)+0.45$ (for clay)	Alpan (1967)
(24)	$D = \lambda\Lambda/(M(1+e_0))$	Ohta (1971)
(25)	$\alpha = \alpha e/(1+e_0)$	Sekiguchi (1977)
(26)	$\dot{v}_0 = \alpha/t_c$	Sekiguchi(1977)
(27)	$\phi' = 0.19\,Lig + 32$ (for peat)	Hayashi (2005)
(28)	$K_i = K_0(OCR)^m$ $m = 0.005Lig+0.45$ (for peat)	Hayashi (2006)

Figure 8 - Procedures of input parameter determination

The estimated parameters used in the analyses of Ebetsu Trial Embankments are summarized in Table 1. The estimated value of permeability coefficient used as the parameter in sand drain area is modified by multiplying the correction factor calculated from the theory by Barron. In this analysis estimated permeability used in sand drained area is about 10 times of the permeability coefficient listed in Table 1(b).

Table 1 - The estimated parameters of Ebetsu Trial Embankment

(a) Non-treated test fill

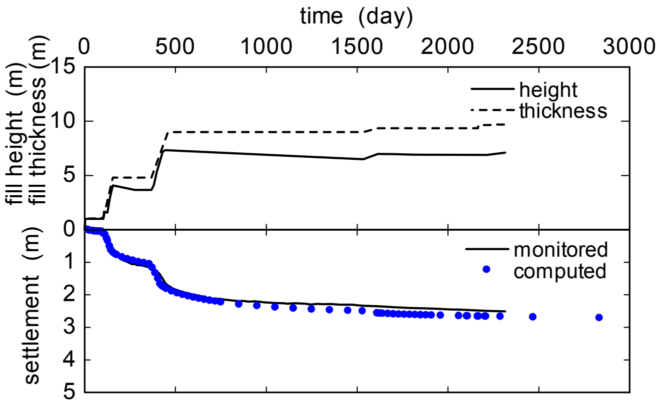
subsoil	constitutive equation	m	m						kN/m²		kN/m²							kN/m³		
		depth	thickness	D	Λ	M	ν	k/γ_w	σ'_{v0}	K_0	σ'_{vi}	K_i	α	V_0	λ	e_0	λ_k	γ_t	lame λ	lame μ
fill material	linear elastic						0.333	8.810E-03			9.90	1.000						19.80	14814	7429
capping	linear elastic						0.333	8.810E-03			9.90	1.000						19.80	3667	1839
sandmat	linear elastic						0.333	8.810E-03			9.07	0.500						18.14	7335	3679
peat (Ap2-2)	elasto plastic	0.0 ~ 0.9	0.9	0.095	0.843	1.887	0.220	9.820E-04	11.30	0.282	4.64	0.582			2.773	11.988	2.773	10.31		
		0.9 ~ 1.6	0.7	0.095	0.850	1.887	0.220	4.195E-04	15.81	0.282	9.46	0.428			2.773	12.092	2.773	10.31		
clay (Am2-2)	elasto-visco plastic	1.6 ~ 3.6	2.0	0.062	0.772	0.940	0.351	3.856E-05	47.43	0.540	17.11	1.344	0.0038	6.104E-06	0.162	1.149	0.162	17.28		
		3.6 ~ 5.6	2.0	0.063	0.779	0.940	0.351	1.911E-05	76.12	0.540	32.05	1.170	0.0038	4.854E-06	0.162	1.152	0.162	17.28		
		5.6 ~ 7.6	2.0	0.063	0.784	0.940	0.351	1.279E-05	100.23	0.540	46.99	1.063	0.0038	4.277E-06	0.162	1.154	0.162	17.28		
		7.6 ~ 8.6	1.0	0.063	0.786	0.940	0.351	1.035E-05	116.25	0.540	58.20	1.003	0.0038	4.015E-06	0.162	1.155	0.162	17.28		
silty sand (As2-2)	linear elastic	8.6 ~ 9.4	0.8				0.333	2.467E-02			65.54							18.82	7488	3755
clay (Am2-2)	elasto-visco plastic	9.4 ~ 10.2	0.8	0.057	0.789	1.000	0.348	8.074E-06	134.43	0.533	72.25	0.933	0.0036	2.755E-04	0.149	1.077	0.149	17.56		
silty sand (As2-2)	linear elastic	10.2 ~ 10.6	0.4				0.333	2.467E-02			96.76							19.54	12481	6259
		10.6 ~ 12.6	2.0				0.333	2.467E-02			108.44							19.54	12481	6259
		12.6 ~ 14.6	2.0				0.333	2.467E-02			108.44							19.54	12481	6259
clay (Am2-1)	elasto-visco plastic	14.6 ~ 16.0	1.4	0.059	0.807	1.040	0.346	2.716E-05	146.42	0.530	123.66	0.617	0.0038	2.208E-05	0.165	1.175	0.165	17.64		
		16.0 ~ 18.0	2.0	0.059	0.808	1.040	0.346	2.203E-05	156.50	0.530	136.97	0.598	0.0038	1.914E-05	0.165	1.176	0.165	17.64		
		18.0 ~ 20.0	2.0	0.059	0.810	1.040	0.346	1.754E-05	167.69	0.530	152.64	0.577	0.0038	1.634E-05	0.165	1.177	0.165	17.64		
silty sand (As2-1)	linear elastic	20.0 ~ 20.6	0.6				0.333	2.467E-02			163.18							18.82	7488	3775
clay (Am1)	elasto-visco plastic	20.6 ~ 21.1	0.5	0.076	0.900	1.070	0.355	1.653E-05	167.80	0.550	167.80	0.550	0.0045	6.337E-06	0.201	1.238	0.201	17.48		
		21.1 ~ 23.1	2.0	0.076	0.900	1.070	0.355	1.527E-05	177.39	0.550	177.39	0.550	0.0045	6.188E-06	0.201	1.238	0.201	17.48		
		23.1 ~ 25.1	2.0	0.076	0.900	1.070	0.355	1.298E-05	192.73	0.550	192.73	0.550	0.0045	5.714E-06	0.201	1.238	0.201	17.48		
		25.1 ~ 27.1	2.0	0.076	0.900	1.070	0.355	1.119E-05	208.07	0.550	208.07	0.550	0.0045	5.320E-06	0.201	1.238	0.201	17.48		
		27.1 ~ 29.1	2.0	0.076	0.900	1.070	0.355	9.705E-06	223.41	0.550	223.41	0.550	0.0045	4.952E-06	0.201	1.238	0.201	17.48		

(b) Sand drain-treated test fill

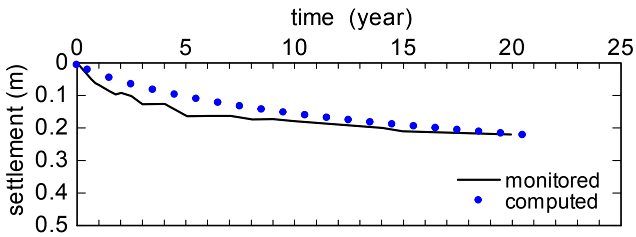
subsoil	constitutive equation	m	m						kN/m²		kN/m²							kN/m³		
		depth	thickness	D	Λ	M	ν	k/γ_w	σ'_{v0}	K_0	σ'_{vi}	K_i	α	V_0	λ	e_0	λ_k	γ_t	lame λ	lame μ
fill material	linear elastic						0.333	8.810E-03			9.90	1.000						19.80	14814	7429
capping	linear elastic						0.333	2.643E-04			4.30	1.000						19.80	3667	1839
sandmat	linear elastic						0.333	8.810E-03			9.07	1.000						18.14	7335	3679
peat (Ap2-2)	linear elastic	0.0 ~ 0.6	0.6				0.220	1.638E-03			3.09	0.665				11.942	2.773	10.31	564	718
	elasto plastic	0.6 ~ 0.9	0.3	0.095	0.845	1.887	0.220	6.567E-04	13.24	0.282	6.26	0.518			2.773	12.027	2.773	10.31		
		0.9 ~ 1.8	0.9	0.095	0.846	1.887	0.220	6.414E-04	13.55	0.282	6.57	0.508			2.773	12.034	2.773	10.31		
clay (Am2-2)	elasto-visco plastic	1.8 ~ 3.8	2.0	0.055	0.770	1.060	0.351	4.763E-05	41.20	0.540	14.27	1.394	0.0038	6.190E-06	0.162	1.149	0.162	17.28		
		3.8 ~ 5.8	2.0	0.055	0.778	1.070	0.351	2.129E-05	71.09	0.540	29.21	1.196	0.0038	4.774E-06	0.162	1.152	0.162	17.28		
		5.8 ~ 7.8	2.0	0.055	0.783	1.080	0.351	1.384E-05	95.91	0.540	44.15	1.081	0.0038	4.187E-06	0.162	1.153	0.162	17.28		
		7.8 ~ 9.0	1.2	0.055	0.786	1.080	0.351	1.074E-05	113.37	0.540	56.10	1.013	0.0038	3.841E-06	0.162	1.155	0.162	17.28		
silty sand (As2-2)	linear elastic	9.0 ~ 9.8	0.8				0.333	2.467E-02			64.19							18.82	7488	3775
clay (Am2-2)	elasto-visco plastic	9.8 ~ 10.6	0.8	0.050	0.789	1.140	0.348	8.261E-06	132.77	0.533	70.90	0.938	0.0036	2.784E-04	0.149	1.077	0.149	17.56		
silty sand (As2-2)	linear elastic	10.6 ~ 12.2	1.6				0.333	2.467E-02			81.21							18.82	7488	3775
clay (Am2-1)	elasto-visco plastic	12.2 ~ 14.2	2.0	0.050	0.804	1.110	0.342	4.173E-05	124.13	0.519	96.67	0.652	0.0034	8.298E-04	0.142	1.065	0.142	18.06		
silty sand (As2-1)	linear elastic	14.2 ~ 14.6	0.4				0.333	2.467E-02			106.72							18.82	4993	2504
		14.6 ~ 15.6	1.0	0.065	0.806	0.940	0.346	3.172E-05	137.48	0.530	112.44	0.635	0.0038	2.824E-05	0.165	1.175	0.165	17.64		
clay (Am2-1)	elasto-visco plastic	15.6 ~ 17.6	2.0	0.065	0.807	0.940	0.346	2.631E-05	146.84	0.530	124.19	0.616	0.0038	2.502E-05	0.165	1.175	0.165	17.64		
		17.6 ~ 19.6	2.0	0.065	0.809	0.940	0.346	2.156E-05	158.62	0.530	139.86	0.594	0.0038	2.215E-05	0.165	1.176	0.165	17.64		
silty sand (As2-1)	linear elastic	19.6 ~ 20.4	0.8				0.333	2.467E-02			151.30							18.82	7488	3775
clay (Am1)	elasto-visco plastic	20.4 ~ 20.9	0.5	0.065	0.813	1.130	0.355	1.864E-05	161.10	0.550	156.83	0.563	0.0045	6.860E-06	0.201	1.237	0.201	17.48		
		20.9 ~ 22.9	2.0	0.065	0.814	1.130	0.355	1.772E-05	165.08	0.550	166.41	0.546	0.0045	6.682E-06	0.201	1.238	0.201	17.48		
		22.9 ~ 24.9	2.0	0.066	0.900	1.220	0.355	1.476E-05	181.75	0.550	181.75	0.550	0.0045	6.126E-06	0.201	1.238	0.201	17.48		
		24.9 ~ 26.9	2.0	0.066	0.900	1.220	0.355	1.257E-05	197.09	0.550	197.09	0.550	0.0045	5.657E-06	0.201	1.238	0.201	17.48		
		26.9 ~ 28.9	2.0	0.066	0.900	1.220	0.355	1.075E-05	212.43	0.550	212.43	0.550	0.0045	5.217E-06	0.201	1.238	0.201	17.48		

3.3. Predictability of settlement and deformation of highway embankment

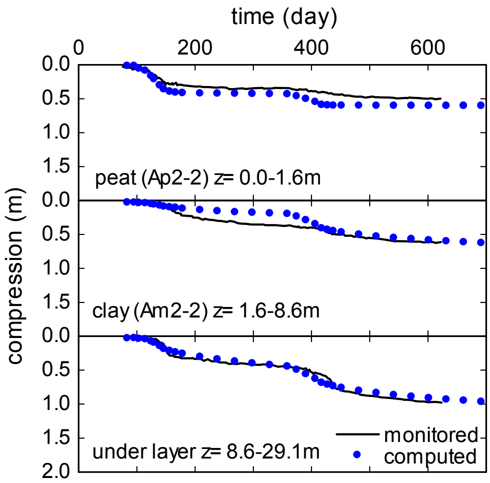
Figures 9 and 10 show the computed results in Ebetsu Trial Embankments being compared with the monitored performance respectively. Those computed results of settlement and compression under the center of embankment agree well with the observed ones during construction period. The computed pore water pressure of each clay layer shows the relatively good agreement with the monitored one. But the computed results of peat are quite higher than the monitored values. The computed long-term settlements for past 20 years are found to be with the sufficient predictive accuracy.



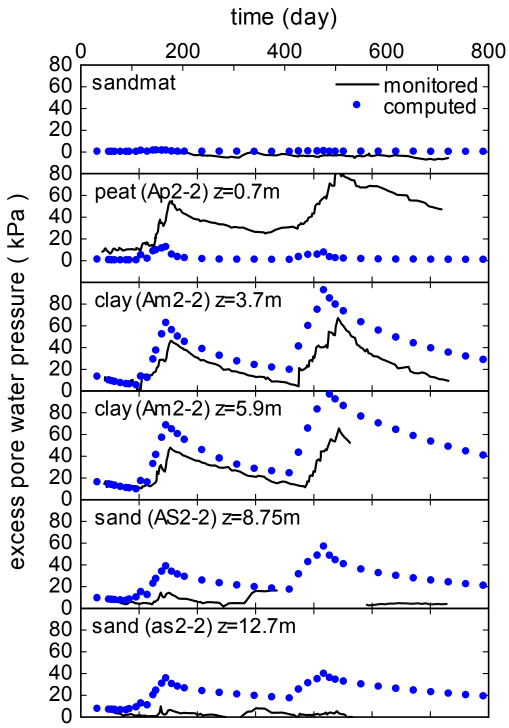
(a) settlement during construction



(b) settlement during operation

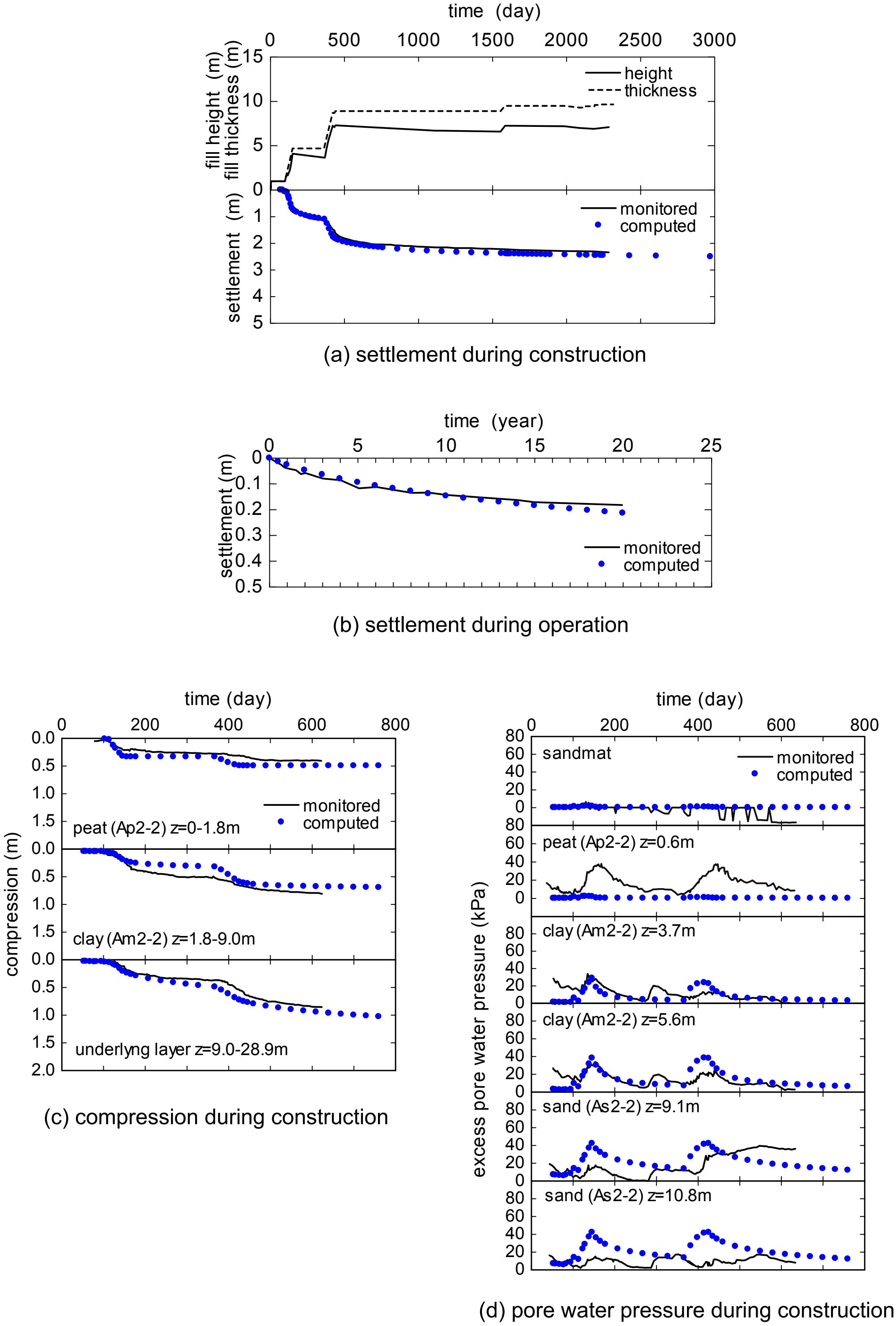


(c) compression during construction



(d) pore water pressure during construction

Figure 9 - Computed results in Ebetsu Trial Embankment (Non-treated test fill)



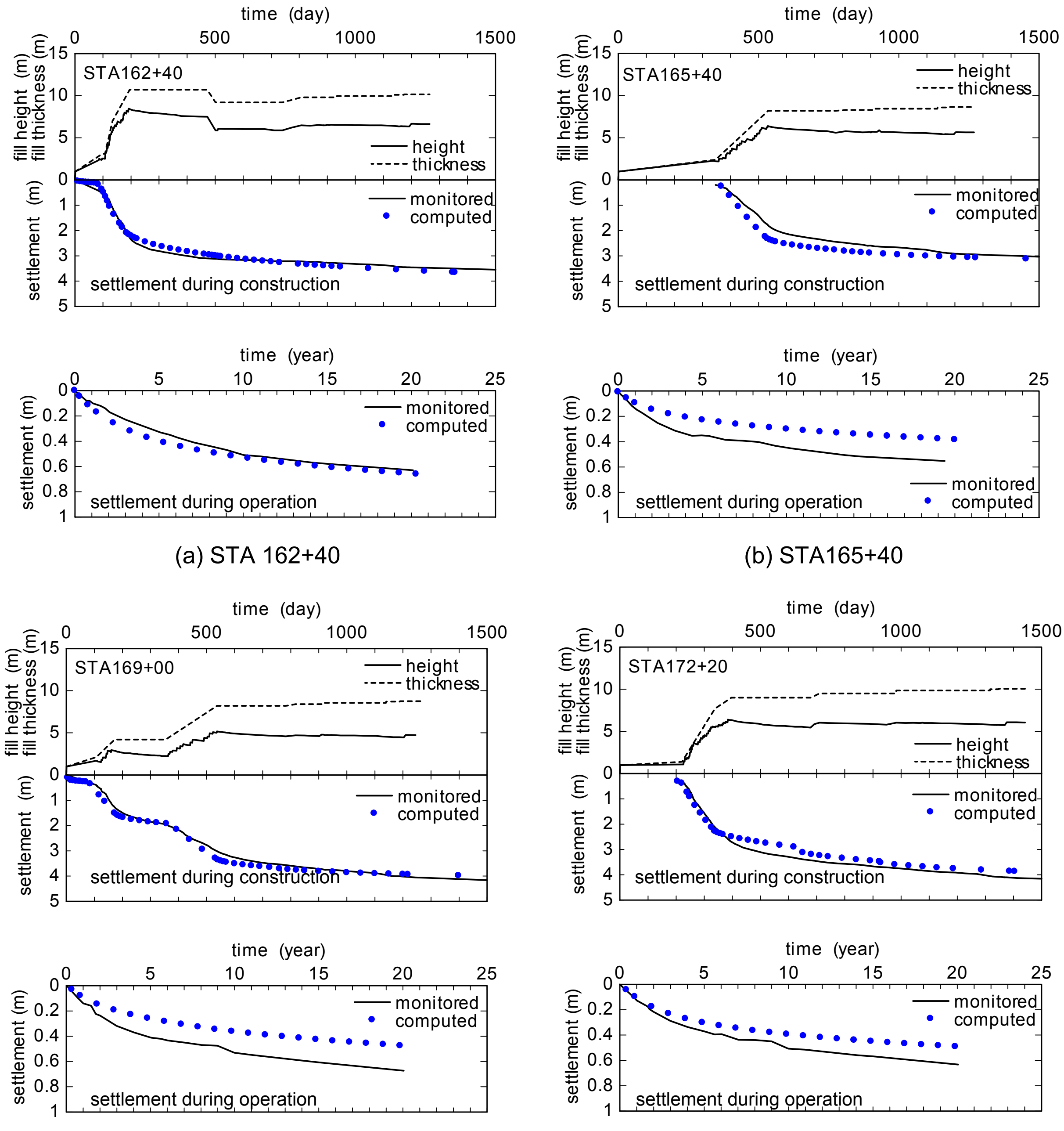
(a) settlement during construction

(b) settlement during operation

(c) compression during construction

(d) pore water pressure during construction

Figure 10 - Computed results in Ebetsu Trial Embankment (Sand drain-treated test fill)



(a) STA 162+40 (b) STA165+40

(c) STA 169+00 (d) STA172+20

Figure 11 - Computed results in Ebetsu-Futo East Works

Figures 11 (a), (b), (c) and (d) show the computed settlements in Ebetsu-Futo east works being compared with the monitored data respectively. The computed settlements during construction period agree well with the monitored ones as same as the analyses of Ebetsu Trial Embankment. However, the predictive accuracy of long-term settlement is getting low compared with the analysis result of Ebetsu Trial Embankment. It is thought that the great influence of the secondary consolidation of peat layer is more than trial embankment. Since this section had little monitored data during construction compared with trial embankment, it is considered to originate in condition assessment having been inadequate.

These analyses show that the long-term settlement and deformation of the highway embankment during operation can be predicted relatively well if the deformation behavior during construction can be successfully simulated. Improvement of the precision of prediction may be done by the condition assessment of ground information, determination of soil parameters and setup of a boundary conditions more realistically.

Although this paper shows only the computed results of settlement, the stress state of the foundation, the dispersion of pore pressure, the stability of the foundation, etc. can be predicted from the computed results. It is thought that these results offer effective basic data in case of not only deterioration prediction of road but the design of the road improvement and upgrading in the future.

4. INDICATOR REPRESENTATIVE OF HIGHWAY EMBANKMENT ON SOFT FOUNDATION

Table 2 shows one of the examples of the relationships between indicators of highway embankment on soft foundation and performance indicator of road. Settlement and deformation of highway embankment reduce the service level of road. The road vertical alignment and the faulting between a bridge abutment and adjacent pavement are investigated as the performance-related indicators relevant to indicators of highway embankment especially.

Table 2 - The relation between indicators of highway embankment and road

Indicator of highway embankment	Performance-related indicator of road	Performance indicator of road
･settlement ･deformation	･vertical alignment ･faulting ･pavement unevenness ･drainage	･traffic delays ･crashes ･vehicle operating cost

5. LIFE-CYCLE COST ESTIMATION OF HIGHWAY EMBANKMENT ON SOFT FOUNDATION

The life-cycle cost estimated based on the analyzed settlement and deformation was compared with the life-cycle cost actually needed in the past 20 years at the section of Ebetu-Futo East Works. The maintenance method to settlement of highway embankment is generally performed by asphalt overlay. Therefore it limits for simplification to the maintenance cost of the pavement caused by settlement of highway embankment in this life-cycle cost estimation.

5.1. Maintenance criteria to service level

The actual maintenance criteria to the service level in this section are both the minimum road vertical alignment and the faulting between a bridge abutment and adjacent pavement set to vehicle speed at 100km/h. Figure 12 shows the allowable settlement as indicator representative related to road vertical alignment. In this section, future excessive settlement was predicted; therefore extra filling of about 0.5 m is adopted as countermeasure. Figure 13 shows the allowable settlement as indicator representative related to faulting between abutment and adjacent pavement. In this section, the rate of change of the vertical slope is adopted as a definition of the faulting, and it is considered as 0.5% or more of the vertical slope of the bridge which is immobility.

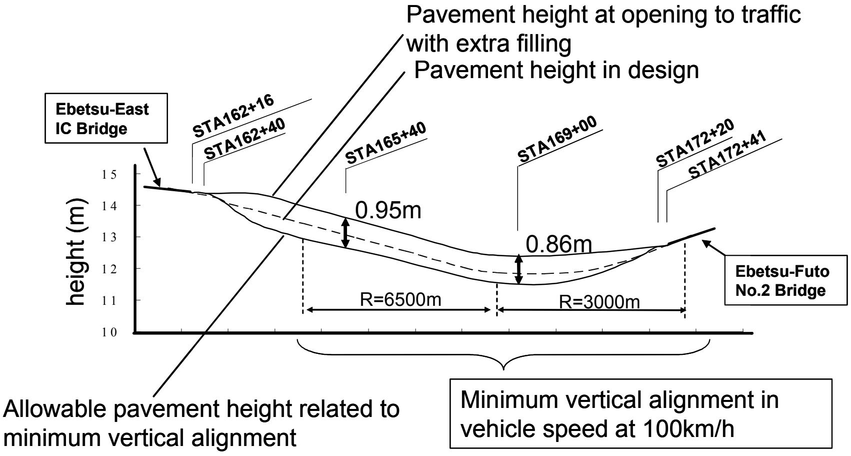


Figure 12 - Allowable settlement as indicator related to road vertical alignment

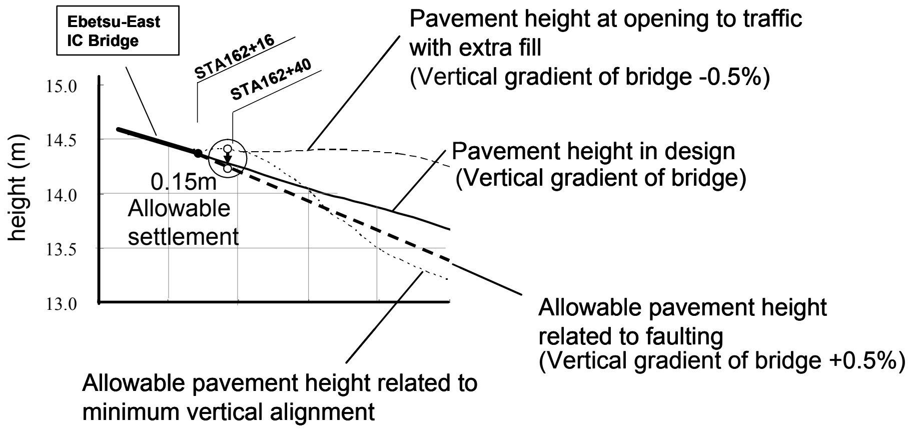


Figure 13 - Allowable settlement as indicator related to faulting

Table 3 - Indicators and maintenance criteria

STA	162+40	165+40	169+00	172+20
Performance related indicators	faulting	minimum vertical alignment	minimum vertical alignment	faulting
Indicators of highway embankment	allowable settlement			
Maintenance criteria	settlement >0.15m	settlement >0.95m	settlement >0.86m	settlement >0.16m

Table 3 summarizes the indicators and the maintenance criteria to the required sevice level set to vehicle speed at 100km/h. Figure 14 shows the structures of pavement in this section as countermeasure which took settlement and rutting by spike raveling into consideration. In this district, since the spike (studded) tires are used in winter seasons, the repair of pavement rutting was performed at 1 time of a rate in about four years. Therefore it is considered as provisional pavement structure for four years from opening to traffic. Adopted is the plan to perform completion pavement structure to serve also as repair for this rutting and settlement. In this life-cycle cost estimation, this cost is taken into consideration.

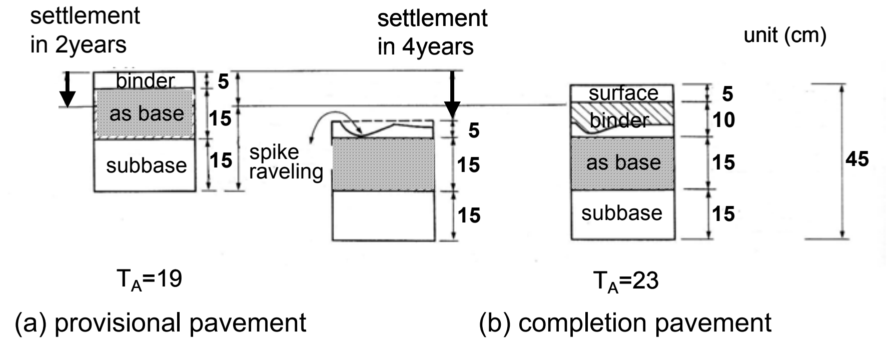


Figure 14 - Structures of asphalt pavement in the section of Hokkaido Expressway

5.2. Performance modelling of asphalt overlay

Figure 15 shows performance model of asphalt overlay which is predicted by computed settlement of STA162+40 as an example. The maintenance criterion to the required service level is an allowable settlement of 0.15m (see Table.4). Shown are the number of times of asphalt overlay for 20 years and timing of asphalt overlay, when allowable settlement is exceeded. The height of asphalt overlay is to the pavement height of the time of opening to traffic shown in Fig. 13 in order to delay next overlay time as same as the actual plan. In Figure 15, in order to examine timing of asphalt overlay, parallel translations of the settlement curve are carried out according to this pavement height. The 3rd overlay is not based on a faulting but based on upgrading for completion pavement shown in Fig. 14. From this model, the asphalt overlay for the past 20 years has been done 5 times, and timing is predicted to be 1st year, 3rd years, 4th years, 8th years, and 19th year after opening to traffic.

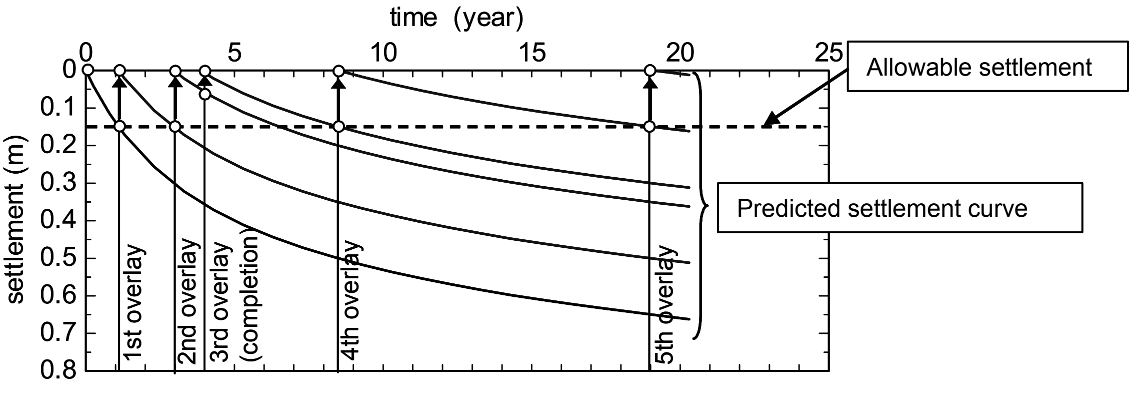


Figure 15 - Performance modeling of asphalt overlay (STA 162+40)

5.3. Life-cycle cost estimation

Table 5 shows the life-cycle of asphalt overlay predicted based on the analyzed settlement compared with the actual life-cycle in the past 20 years at the section of Ebetu-Futo East Works. The predicted life-cycle of asphalt overlay relatively agrees well with actual ones. In the case of STA172+20, the predicted times of asphalt overlay are evaluated less than actual ones. This is because computed settlement is less than actual settlement. In the case of STA165+40 and STA169+00, asphalt overlay related to road vertical alignment is not performed both predicted and actual results since the settlement does not exceed the maintenance criterion. The extra filling of the fill body was found to be seen the effective countermeasures to reduce maintenance costs of highway embankment on soft foundation.

Table 5 - Predicted and actual life-cycle of asphalt pavement for 20years

STA	Predicted		Actual	
	Times of overlay	Timing of overlay (year)	Times of overlay	Timing of overlay (year)
162+40	5	1st,3rd,4th,8th,19th	5	1st,2nd,4th,6th,9th
165+40	1	4th	1	6th
169+00	1	4th	1	6th
172+20	4	1st,3rd,4th,15th	6	1st,2nd,3rd,4th,6th,11th

Table 6 shows the life-cycle cost estimated based on the analyzed settlement is compared with the life-cycle cost actually needed in the past 20 years from 1983 to 2003 at the section of Ebetu-Futo East Works. In both of the estimation, the maintenance cost for the faulting is assumed to be 5 million yen per time and cost for vertical alignment correction is assumed to be 100,000 yen per 1m of length in four lanes. The discount rate used in this estimation is from 3 to 9 percent and the cost is adjusted for the present value for which base year is set in 1983. The predicted life-cycle costs successfully agree well with actual ones.

Table 6 - Predicted and actual life-cycle cost of asphalt overlay for 20years

Discount rate	(a) Predicted LCC (yen)	(b) Actual LCC (yen)	(a)/(b) (%)
3%	129,000,000	140,000,000	92.1
5%	118,000,000	126,000,000	93.6
7%	109,000,000	113,000,000	96.4
9%	101,000,000	102,000,000	99.0

6. CONCLUDING REMARKS

Presented are the indicator representative of highway embankments on soft foundation and the applicability of soil - water coupled finite element analysis as a tool for supporting road asset management. The soil-water coupled analysis gives values very close to those monitored at the two trial embankments and four actual embankments during construction and operation for the past 20 years and its predictability was verified. A set of indicators describing the long-term deformation of highway embankment on soft foundation may be a sort of promising indicators related to indicators of asphalt pavement and road. Life-cycle cost based on this analysis successfully agrees with actual one. The proposed asset management sub-system is fully promising to support asset management of highway embankment on soft foundation.

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