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Ex-Post-Facto estimate of performance at the offshore reclamation of airport Osaka/KIA

L'estimation Ex-Post-Facto de la performance des remblais amendes sur la mer de l'aéroport d'Osaka/KIA

K. Akai
Kyoto University, Japan

Y. Tanaka
Research Center for Urban Safety and Security, Kobe Univ., Japan

ABSTRACT
Reliability analysis was performed on the settlement performance of the first stage construction of KIA (Kansai International Airport). The analysis is based on the settlement measurements that are taken over the nine years period starting from the end of 1993, and also based on the soil investigation results for the Upper-Most Pleistocene Clay (Ma12). Based on the analysis, a possible range of future settlements, in probabilistic terms, of both the total and of the Ma12 stratum over the next 50 years is given. Also given is an evaluation on the performance of PTB (Passenger Terminal Building) of KIA that was made by examining the maintenance records of the differential settlement adjustments of its foundations.
In essence, the main objective of this paper is to present a quantitative analysis based on the probabilistic approach on the ambiguities of obtained settlement data and soil testing data. Therefore the prediction presented in this paper belongs to the Type B prediction as proposed by Lambe.

RÉSUMÉ
Une analyse de fiabilité a été faite sure la performance au tassement de la première phase de construction de KIA (Kansai International Airport). Cette analyse est fondée sur des mesures de tassement obtenues sur une période to neuf (9) années à partir de la fin de 1993 ; l'analyse inclue aussi les résultats d'une étude de sol de la couche d'argile Pléistocène supérieure (Ma12). Basée sur cette analyse, une projection probabiliste du tassement de la couche Ma12, ainsi que de tout le site, sur une période future de 50 ans est dérivée. Une évaluation des effets de tassement sur la performance de l'Aérogare des Passagers (Passenger Terminal Building) de KIA est aussi produite en examinant les données sur les ajustements de niveau des fondations du bâtiment effectues par les techniciens de maintenance. L'objectif principal de cette étude est de présenter une analyse quantitative et probabiliste des incertitudes associées avec les donnes de tassement et des essais de sol. Par conséquent, les prédictions présentées dans cette communication appartiennent à la Prédiction Type B proposée par Lambe.

1 INTRODUCTION

Kansai International Airport was constructed by reclaiming the off-shore of Osaka Bay by placing granular fill with a height of about 33 metres on the seabed. Construction began in January 1987 and most of the reclamation work was completed by December 1991. Construction of the airport facilities followed and the airport began operations in September 1994. The major construction challenge was management of the long-term consolidation settlement of deep seated Pleistocene clays. The superficial soft alluvial clay of about 20 metres thick has been improved by sand drains, and the settlement has nearly ceased during the construction.

Figure 1 shows the geotechnical condition of seabed beneath the airport. The Pleistocene clay comprises 7 major clay layers, plus additional layers of varying materials, and the current average settlement of the airport is approximately 11 metres. Compression of the Pleistocene deposits is approximately 5.5 metres and is still continuing but at a decreasing rate. Settlement has been monitored at a number of locations and it is apparent that the consolidation behavior of these thick, natural clays is very complex due to the limited drainage capacities of the interlaced sand and clay layers, and the compression characteristics of the aged clay; these factors cannot be accounted for by the conventional Terzaghi type of soil model. The very high compression behavior at stresses just above the preconsolidation pressure, due to the de-structuring of the cemented clay fabric, is especially difficult to predict. Highly variable geotechnical properties within each clay layer add further uncertainties and complications in the prediction of settlement.

In view of these uncertainties it is appropriate, and of significant value, to examine the reliability of settlement prediction at the site. This paper evaluates predictions of further settlement at the site based on a probabilistic approach. The causes of uncertainty in settlement predictions for these Pleistocene clay layers, based on the observed data and on the range of predicted settlement, are discussed. Also discussed are the settlement

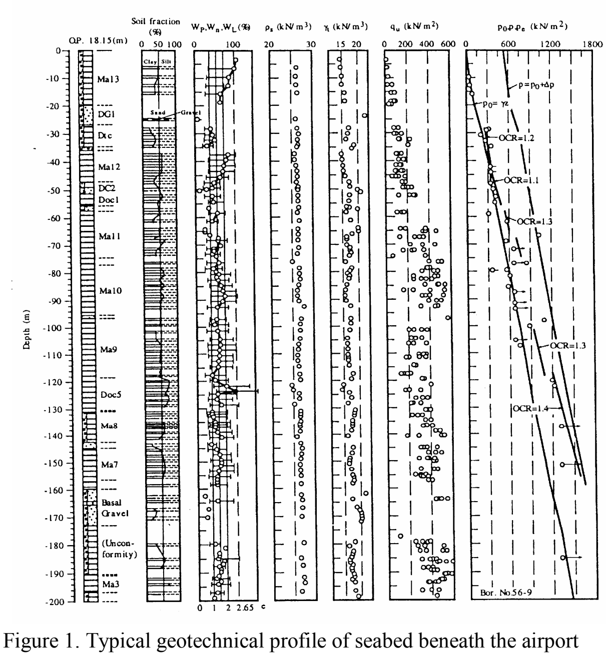

Figure 1. Typical geotechnical profile of seabed beneath the airport

problems and adjustment measures taken at the Passenger Terminal Building (PTB) that are due to the large consolidation settlement at the airport.

2 RELIABILITY ANALYSIS ON COMPRESSION OF MA12 PLEISTOCENE CLAY LAYER

First, we will examine the reliability of settlement prediction by focusing our attention to the uncertainties in the compression properties of Ma12 clay which is the upper-most and most compressible stratum among the multiple layers of Pleistocene clays beneath the airport. The study is to examine how the uncertainties in soil parameters affect the reliability of predicted settlement. A large database of soil explorations and tests has been constructed for the Osaka Bay marine clays, and this database is readily available for the research studies as has been described by Akai et al. (1995).

The soil exploration results usually yield a considerable amount of data scattering, and therefore the geotechnical assessment utilizing the probabilistic approach is superior to the deterministic one to fully reflect the variability of exploration results. For the engineering designs, precise geotechnical design parameters are nearly impossible to obtain, and therefore it is more desirable to assess the reliability of geotechnical parameters and also to refine of the analysis accordingly. In the followings, described are the settlement predictions and its reliability that are based on the probability theory of FOSM (First Order Second Moment) method as given by Ang and Tang (1984).

1) Simple prediction based on $S = H\dfrac{\Delta e}{1+e_0} = H\dfrac{e_0 - e_f}{1+e_0}$

The geotechnical parameters for Ma12 are defined as shown in Table-1 based on the analysis using the geotechnical database as described previously.

Table 1. Geotechnical Parameters for Ma12

	Aveage	Coeff. of Variance	Standard Deviation
N	1	0.1	0.1
H	1,070cm	0.05	53.5
e_o	2	0.1	0.2
e_f	1.5	0.15	0.225

Then the performance function is defined as follows;

$$g(X) = S_{target} - NH\frac{e_0 - e_f}{1+e_0} \cdots\cdots \quad (1)$$

where N denotes the uncertainty of equation used.

Table 2 summarizes the results of FOSM analysis, and the most probable amount of settlement predicted is S=178.3cm as shown in Table 2.

Table 2. FOSM Analysis of Compression of Ma12

Reliability index $\beta = \mu_g/\sigma_g$	0	0.05	0.1	0.5	1	1.25
Probability of failure P_F	0.5	0.48	0.46	0.31	0.16	0.11
S_{target} (cm)	178.3	173.8～182.8	169.6～187	134.6～222	92.7～263.9	72.1～284.5

2) Detailed settlement prediction based on

$$S = \sum_{i=1}^{n}\frac{C_c}{1+e}\log\left(\frac{p_0+\Delta p}{p_c}\right)dH = \sum_{i=1}^{n}\frac{C_c}{1+e}\log\left(\frac{p_0+\Delta p}{\mathrm{OCRx}p_0}\right)dH$$

In order to perform a probabilistic settlement analysis for the Pleistocene clay stratum, a simple but reasonable mechanical model is required which reflects the observed compression behavior of the clay. The followings are thought to be typical for the clay; 1) Compression at stress levels below the preconsolidation pressure, p_c, is very small in comparison with that at stress levels above pc, (Akai et al. 1995) and 2) overconsolidation of the clay is due to delayed consolidation and, therefore, the *OCR* value should be constant with depth for the stratum.

In the above equation, there are three geotechnical parameters (*Cc, e,* and *OCR*) plus three geometric or loading parameters (p_0, *dp*, and *H*). After examining the variances in these six parameters, the probabilistic settlement analysis can be performed by evaluating the variation of the following performance function;

$$g(x) = S_{taget} - N\frac{C_c}{1+e}\log\left(\frac{p_0+dp}{OCR\ p_0}\right)H \cdots\cdots \quad (2)$$

The probabilistic settlement analysis of clay stratum Ma12 was performed using available data from near Point 2-6, and at this point the thickness of layer Ma12 is 10.7m. For computational purposes the layer was divided into 10 sub-layers of 1m thickness with a bottom sub-layer of thickness 0.7m, and input parameters of *Cc, e, OCR,* p_0,, *dp* are obtained from the geotechnical database. Table-3.1 lists the geotechnical parameters for each sub-layer, and Table 3.2 presents the average, coefficient of variable, and standard deviation of the parameters at the depth of 32-33meters.

The predicted amount of compression for Ma12 using the average values is S=179.6cm, and this is very close to the value of S=178.3cm as predicted in the simple method using Equation (1). It is to be noted that the actual compression of Ma12 for the period of 9 years (i.e., measurement at the end of 2002) is 1.6m.

Table 3.1. Geotechnical Parameters for sub-layers

z (m)	e	Cc	OCR	p_o (t/m^2)	dp (t/m^2)	H (m)	Settlement (m)
32-33	2.285	1.886	1.35	21.32	43	1	0.201
33-34	2.26	1.86	1.35	21.8	43	1	0.196
34-35	2.221	1.821	1.35	22.29	43	1	0.19
35-36	2.169	1.767	1.35	22.78	43	1	0.184
36-37	2.103	1.699	1.35	23.26	43	1	0.178
37-38	2.023	1.617	1.35	23.75	43	1	0.17
38-39	1.929	1.522	1.35	24.24	43	1	0.163
39-40	1.823	1.413	1.35	24.72	43	1	0.154
40-41	1.702	1.289	1.35	25.21	43	1	0.144
41-42	1.568	1.152	1.35	25.7	43	1	0.133
42-42.7	1.421	1.002	1.35	26.18	43	0.7	0.084
					Total	=	1.796 m

Table 3.2. Variation of Geotechnical Parameters

	Average value(μ)	Coeff. of variance(σ/μ)	Std. deviation (σ)
N	1	0.1	0.1
a	1.32 (yr/m)	0.0145	0.0191
b	0.17 (1/m)	0.0153	0.0026

3 PREDICITON OF FINAL SETTLEMENT BASED ON HYPERBOLIC FITTING WITH RELIABILITY ANALYSIS

In this section, the settlement and time relationship is to be expressed by using the Hyperbolic curve fitting method proposed by Kondner (1963). Akai (2000) has shown that, through the comparison between Hyperbolic method and Terzaghi theory, the Hyperbolic method yields the settlement (i.e., average degree of consolidation) versus time curve in a very good agreement with Terzagi theory up-to 90-95 % of consolidation, but it results in the final settlement about 15 to 20% larger than that of Terzaghi theory.

The Pleistocene Clays in KIA area is in an over-consolidated state due to the delayed consolidation as noted earlier, thus these clays show significant secondary compression when it is subjected to stress level above the pre-consolidation stress, p_c . Thus the Hyperbolic method would be very useful for representing the amount of consolidation settlement including such secondary compressions, Akai and Tanaka (2004).

In the following, the Hyperbolic method is used to predict the settlement and time behavior. The reliability of the Hyperbolic method depends on the accuracy of parameters used in fitting the model, and "a" and "b" are the model parameters. Thus the target values of settlement prediction can be evaluated by assessing the variation of the following performance function;

Table 4. Variation of Fitting Parameters

Average at	$e=$	$Cc=$	OCR=	$p_o=$	$dp=$	$H=$
$z=32$m	*2.285*	*1.886*	1.35	*21.31*	*43*	1m
Coef. of variance	0.047	0.166	0.164	0.023	0.05	0.05
Std dev	0.106	0.313	0.221	0.5	2	0.05

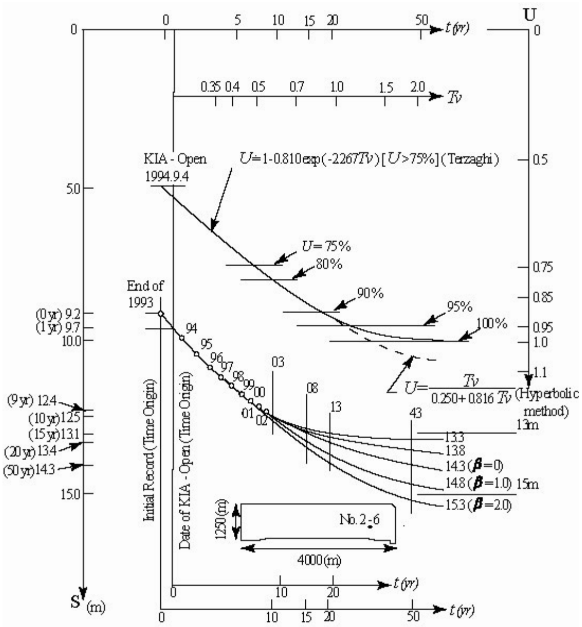

Figure 2. Predicted total settlements of the airport for various indices of reliability.

$$g(x) = S_{target} - N \frac{t}{a + bt} \cdots (3)$$

The variation of parameter to represent the reliability of Eq. (3) is given in Table 4, based on the curve fitting of measured data to that of Hyperbolic curve for the range of 75%<U<90%.

For FOSM analysis, it is necessary to evaluate the reliability safety index, β , of the performance function by locating the most probable failure points for the target prediction value, the amount of settlement at various time "t" for this case.

Figure 2 represents the predicted amounts of settlement for various values of reliability safety index. The total settlement measured at the year end of 1993 was 9.2m, inclusive of consolidation settlement of upper alluvial clay (Ma13) that has been completed. The Hyperbolic curve fitting to the measured settlement-time relationship is made based on the data starting at the end of 1993. It is seen that there is no deviation between the prediction and the measurement up-to the end of 2002.

The total predicted settlement is 14.3 metres at 50 years after the start of curve fitting, that is the year of 2043 (49 years from the opening of the airport). It is shown that the prediction has a possible deviation of ±0.5m for a reliability safety index β of 1.0 (i.e., 16% probability of failure) and a possible deviation of ±1.0m for a value of β of 2.0 (i.e., 2.3% probability of failure).

Figure 3 shows the dissipation of excess pore water pressures with time for the Pleistocene Clay layers beneath an observation point 2-6 at the airport, Akai & Tanaka (1999). The measurement up-to the mid year of 2003 is depicted. It is seen clearly that there is a delay in the dissipation of excess pore water pressure in the lower Pleistocene clays, but the degree of consolidation of Ma12 layer, which is the most dominant compression layer among the Pleistocene layers, is thought to have reached at least 80 to 85% of consolidation. The settlement prediction based on the Hyperbolic method as described above is therefore applicable as the prediction is based on the measured settlement data well beyond the required degree of consolidation.

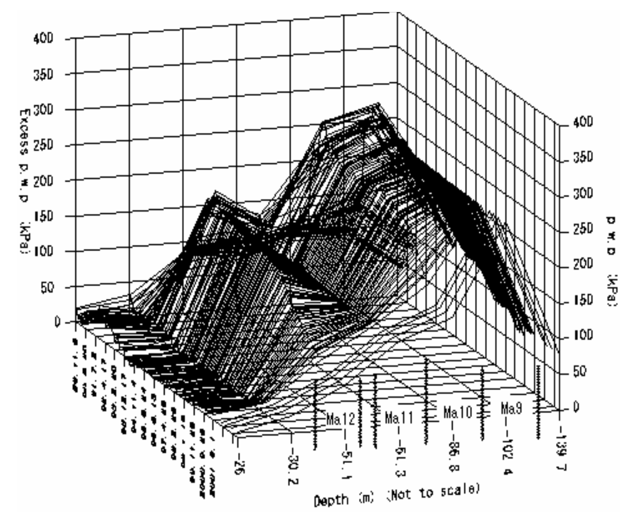

Figure 3. Excess pore water pressure distribution beneath the airport

4 ADJUSTMENTS OF IRREGULAR SETTLEMENTS AT PASSENGER TERMINAL BUILDING

Passenger Terminal Building (PTB) is the key & main service building for a smooth and safe flow of passengers and it has a floor area of 300,000m^2. Figure 4 shows the outline of PTB building. PTB consists of a 4 stories central building (3flr. above ground and 1 basement) with a size of 320m length and 150m across and two wing buildings (3flr. above ground) with a size of 670m length and 40m across each. The total length of these building is 1,660m that are supported by 874 columns, settlement measurements are taken at 576 points.

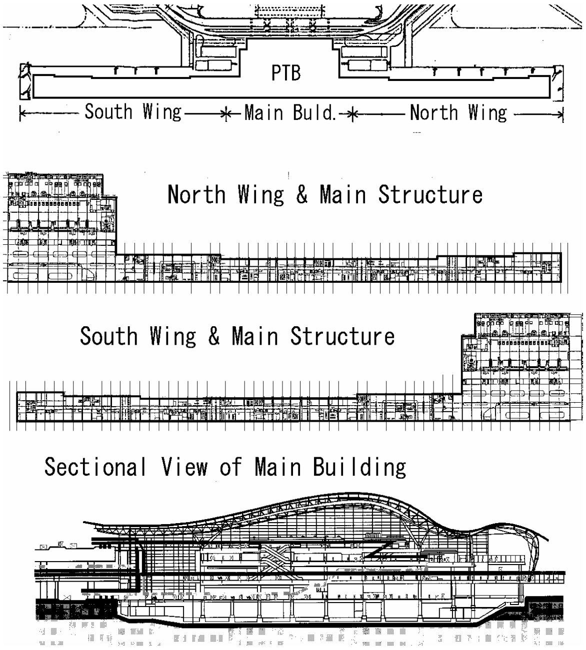

Figure 4. Outline of Passenger Terminal Building

The allowable limits of deformation for upper frame-structure of PTB are set by considering the various aspects, such as design, functions, structural aspects as well as the serviceability of main facilities. The following deformation criteria have been adopted for PTB through structural, architectural, and service planning;

Local distortional angle

θ =1/400 (2.5 x 10^{-3} radian) for main frame structures,

θ =1/600 (1.67 x 10^{-3} radian) for wing roof structures,

Overall distortional angle

α=1/1000 (1.0 x 10^{-3} radian) for main frame structures,

In order to keep the deformations within these criteria, the required amounts of jack-up adjustments of columns are estimated beforehand, and the actual jack-ups are performed. It is however difficult to maintain the PTB alignment absolutely horizontal, and therefore a straight alignment was kept by allowing some inclination relative to the horizon.

In last few years, the adjustments of column levels were made two to three times per year by jack-ups and inserting thin-plates (Matsui et al. 2003).

In this study, we have examined the settlement profile of PTB after the adjustments and review their performance with respect to the distortion criteria as described before. Figure 5 shows the settlement profile of PTB as of Oct. 2003 after the jack-ups and that of surrounding ground. It is clearly seen that the differential settlement of about 95cm has occurred between the center of PTB and the maximum settlement point of the wing building. The comparison between the distortion criteria and the actual performance has given the following observations;

1) The maximum distortion has occurred at the boundaries between the main and the wing buildings. The observed local distortional angles were 1/450 and 1/420 at south and north boundaries respectively, and these values exceed the design criteria of 1/600.
2) On the other hand, the overall distortional angles of PTB were 1.1/1000 and 0.98/1000 at the south and north wing structures respectively, and these have nearly reached the design criteria of 1/1000.

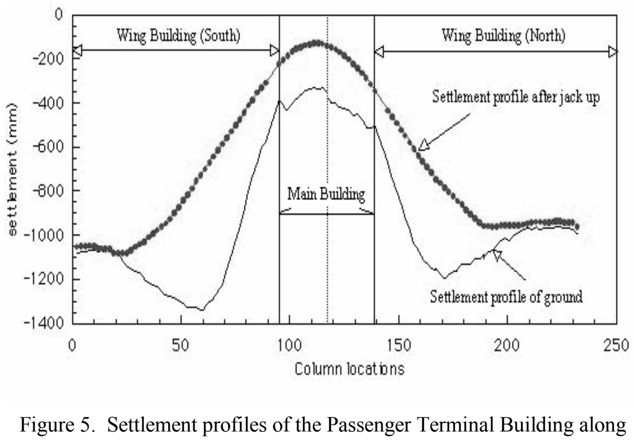

Figure 5. Settlement profiles of the Passenger Terminal Building along the longitudinal direction.

5 CONCLUSIONS

Based on the studies described herein, the following conclusions may be drawn;

1) Two different reliability analyses of consolidation settlement of Ma12 layer has yielded reasonable agreement between a model based on more rigorous analysis using 6 parameters (*Cc, e, OCR,* p_o*, dp, H*) and a simple analysis using 3 parameters. The actual compression of Ma12 as measured in the field showed a good agreement with these analyses.
2) The settlement prediction of Point 2-6 using the Hyperbolic Method with a reliability analysis has given the total settlement of 14.3m with ±0.5m error for the reliability index of 1.0 and ±1.0 error for the reliability index of 2.0.
3) The adjustments of differential settlement of PTB using jack-ups have been reviewed by comparing the actual settlement profile measured at Oct., 2003 against the pre-set design criteria for distortional angles. It showed that the maximum local distortions are found at the boundaries between the wing and the main buildings, and these values exceed the design criteria. On the other hand, the overall distortion of PTB has nearly reached the pre-set design criteria.

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