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Continuous River Levee Safety Assessment Based on a Reliability Analysis

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Abstract. A design scheme is proposed to evaluate the safety of continuous linear structure *i.e.* river levee. The scheme is developed to establish a procedure to continuously evaluate the stability failure of embankment during flood runoff by seepage, and to identify locations for reinforcement of river levee. A 20km stretch of a fairly large river running through one of the major cities in Japan is chosen for a case study. First all the information available for this river levee for the both side of river have been collected and complied. The data include river levee configurations for every 200m, all the soil investigation results done in the past and the results of levee safety inspection by MLIT. The strength parameters of the embankment and the foundation are obtained from about 50 triaxial test results (CUbar). The permeability coefficient is estimated from about 300 grain size distribution and 15 permeability test results. The configurations of the levee sections are analyzed, and the ranges of various dimensions, such as slope inclinations, crown width, height of retaining wall at edge of slope *etc.*, are obtained. Based on these information, detailed seepage and stability analyses for the possible dimensions of levee sections and material properties are carried out to get the response function (RS) for the safety assessment. Based on this information, the response surface (RS) for the river levee is developed. In developing RS, the experimental design technique is applied for efficiency. MCS is applied to evaluate the failure probability of the levee based on the parameters obtained from the all the analyses explained above for every 200m interval along the levee because all the configuration dimensions of the levee is available at these sections. Results of MCS are presented along the levee, which immediately shows less safe sections.

Keywords. Levee safety, seepage failure, piping, reliability analysis, statistical analysis, response surface

1. Introduction

The Japanese government has started a new scheme of river levee safety inspection from 2002. In this scheme the governmental managed river levee, whose total length is more than 10,000 km, has been inspected (Honjo, Mori, Ishihara and Otake, 2015).

The first round of the inspection for the seepage stability has been completed by 2009. It was found only 60% of 10,000 km, long governmental managed river levee is judged to be safe. One of the remained issues in this inspection procedure is the employment of the idea of the *continuous strip* (CS). The CS is set to make the inspection more efficient. It is a stretch of river levee whose typical length is from several hundred meters to a few km whose configurations, geological and topological conditions are similar. A *representative cross section* (RCS) is selected for each CS. It is for this RCS that the inspection calculation is made. It is important to know that once the RCS is judged to be NG (no good), all the stretch of the CS is judged to be NG. This makes it difficult to identify the levee section where reinforcement is really required.

This paper tries to resolve the issue above. The seepage safety of levee should be inspected in shorter interval so as to identify the sections of levee that requires reinforcement for seepage failure. .

It is widely recognized that safety evaluation of levee is difficult because it is a structure built over a long period of time: Different materials as well as construction methods are employed in a same cross section. In addition, the quantity of soil investigation is not sufficient to identify detailed soil profile. Furthermore in most of the cases, the spatial fluctuation of the soil strength parameters and the permeability are not properly taken into account in levee seepage and stability calculations.

In this paper, a 20km stretch of a fairly large river running through one of the major urban areas in Japan is chosen for a case study. The 20 km stretch of levee for the both sides of the river is taken as an example to continuously assess its safety against the seepage failures.

The main idea of the continuous assessment is to use river cross section survey that is done in every 200 m interval. The all governmental managed river have this survey record in Japan, thus one can get detailed dimensions of the levee at every 200m. It will be shown in the next section that not only soil profiles and mechanical parameters but also the dimensions of the levee control the seepage failure of levee. A response surface (RS), which is a function that relates the safety factor for critical circular slip surface during a flood to soil properties and dimensions of levee is developed first for this river levee. At the same time, the uncertainties are quantified for soil strength and permeability along the levee. Eventually, all these information are put together to assess the river levee safety along the both side of river banks in continuous fashion.

In the next section (section 2), a sensitivity analysis of factors affecting the seepage failure of levee is done. Also, variation of each factor is identified for the example case. In section 3, a response surface (RS) is built. Finally, the continuous reliability assessment is done for the levee, followed by some discussions in section 4.

2. Factors Controlling Seepage Failure of Levee and Their Uncertainty

2.1. Variation of River Levee Dimensions

The river levee under study, whose length is 20 km, is separated into 17 CS (continuous strips) in the left bank and 16 CS in the right bank. In this paper we will only focus on the left bank of the river.

By superposing the section survey results that have been obtained for every 200m, we have found the configurations of the levee can be classified into 4 categories, and 4 representative sections are chosen for detailed study (**Figure 1**):

Type 1: The levee distributes from 3.6 km to 5.4 km. The average gradient of the back slope is about 1 to 3, and there is about 2 m high retaining wall at the edge of the slope.

Type 2: The levee around 6 km. The average gradient of the back slope is 1 to 3, but partly 1:2. There is a berm near the crown, and retaining wall at the edge.

Type 3: The levee in the midstream from 8.0 km to 10.0 km. 1 to 3 slope gradient and no berm nor retaining wall.

Type 4: The levee in the upstream between 13,2 km to 14.0 km. The back slope gradient is 1 to 2 with berm.

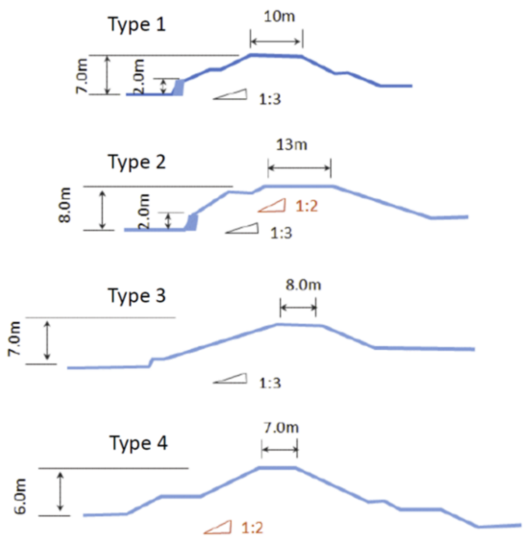


Figure 1 Classification of levee configurations

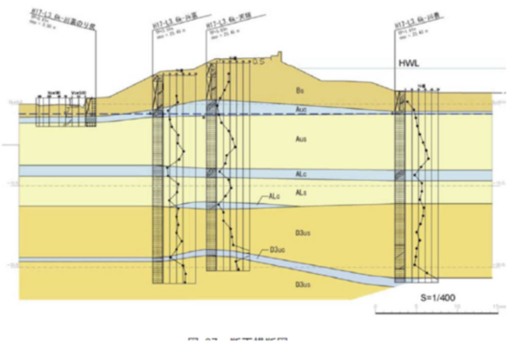


Figure 2 Soil profile at 3.6 km

The soil profile at 3.6 km is presented in **Figure 2**. The embankment is built by sandy soil which most probably be taken locally from the river bed. The foundation consists of a thin clayey layer (Auc) underneath by a thick sandy layer (Aus). In some locations, Auc layer is missing. The foundation soil profile is relatively similar all along the river.

Notations of various dimensions of levee are given in **Figure 3** and their statistics in **Table 1.**

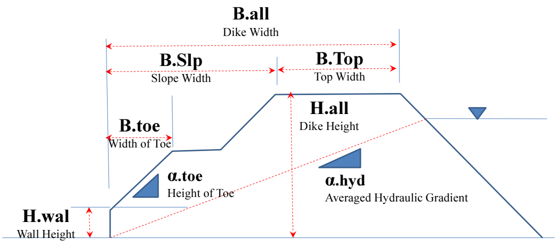


Figure 3 Notations of the dimensions of levee

Table 1 The dimension statistics

Item	Nota.	data	mean	s.d.
Toe slope gradient	α.toe	170	2.41	0.63
Toe slope height (m)	H.toe	172	3.34	1.86
Ave hydraulic grad.	α.hyd	170	0.16	0.07
Wall height (m)	H.wal	142	1.19	0.69
Bank width (m)	B.all	170	26.36	7.08
Bank height (m)	H.all	172	6.15	1.75
Crown width (m)	B.top	143	9.26	3.96
Toe slope width (m)	B.toe	172	8.19	5.39
Back slope width (m)	B.slo	171	16.79	6.06

The average hydraulic gradient is height of river water at its high water level from the base of the embankment divided by the base width of the embankment. It will be discussed later that the important dimension parameters are α.toe, α.hyd, B.toe, B.all and H.wal.

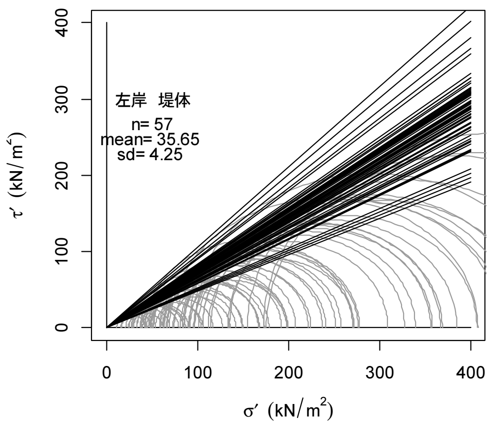
2.2. Spatial Variability of Soil Properties

All the collected soil test data are compiled in the research. Number of results obtained for each type of test is presented in **Table 2.**

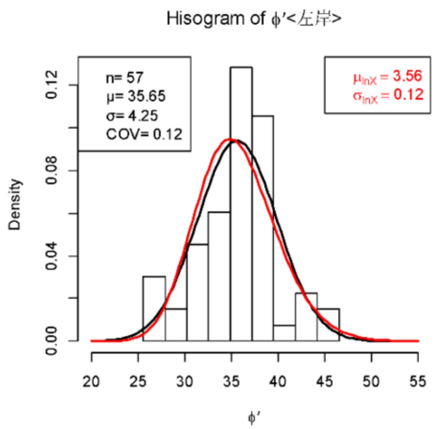
The soil strength for the sandy embankment material, Bs, is evaluated from CUbar tests, whose results are plotted in **Figure 4.** It is interesting to find COV of ϕ' is only 0.12.

Table 2 Number of compiled soil test results

		Left bk.	Right bk.
Triaxial compression test	UU	16	18
	CUbar	57	83
	CU	4	0
	CD	12	6
Sieve analysis	Bs layer	129	160
	Bc layer	22	31
	Aus layer	119	19
	Auc layer	36	46
permeability test (laboratory test number)	Bs layer	15(14)	16(15)
	Bc layer	3(3)	2(2)
	Aus layer	19(7)	36(5)
	Auc layer	0	3(1)

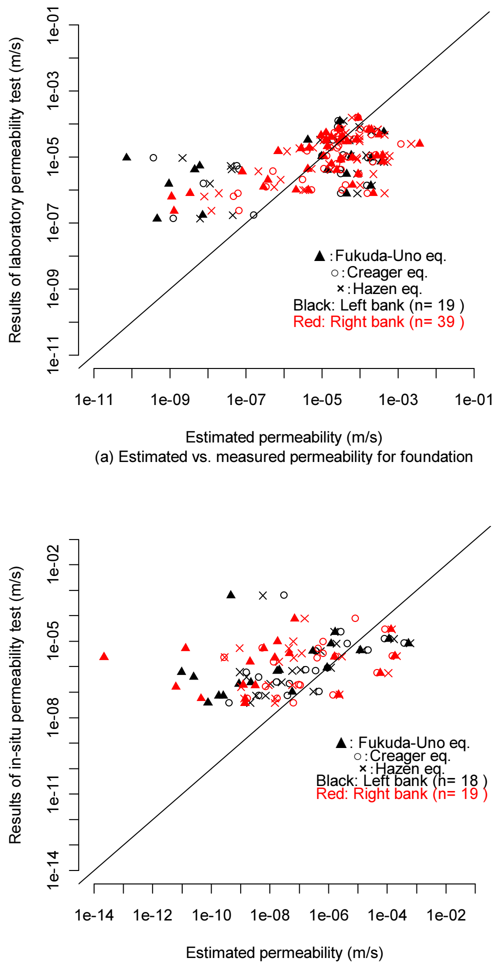


(a) CUbar Mohr's effective stress circles



(b) ϕ' frequency distribution for CUbat tests

Figure 4 CUbar results (the left bank)



(a) Estimated vs. measured permeability for foundation

(b) Estimated vs. measured permeability for embankment

Figure 5 Estimated vs measured permeability

From the grain size distributions of foundation soil (Aus) and the embankment soil (Bs), permeability is estimated by Fukuda-Uno, Creager and Hazen equations. The results are compared with the permeability tests, whose results are presented in **Figure 5**. The estimation equations tend to give larger variability of permeability, but the permeability test results have less scatter which lie in the range of 10^{-4} to 10^{-6} (m/sec) for Aus and 10^{-5} to 10^{-7} (m/sec) for Bs. It can be generally said that the estimates based on the grain size distribution are lower than the measured values.

3. Building a Response Surface

3.1. A procedure to build a RS

The steady state seepage analysis is used to obtain the phreatic surface in levee at the specified high water level. The circular slip line method is used to obtain safety factor, Fs, of the back slope.

As the result of some preliminary analyses, the parameters controlling the safety factor are found to be the friction angle of Bs soil (ϕ'), the ratio between permeability of Bs soil and that of the Aus soil (ke/kb), toe slope gradient (α.toe), average hydraulic gradient (α.hyd), toe slope width (B.toe), bank width (B.all) and toe retaining wall height (H.wal). The statistics of these parameters are listed in Table 3.

Table 3 The statistics of controlling parameters

parameters	notation	mean	s.d.
Friction angle (degree)	ϕ'	36	4.1
Permeability ratio	ke/kb	1.0	0.79
Toe slope gradient	α.toe	2.4	0.63
Ave. hydraulic grad.	α.hyd	0.16	0.07
Toe slope width (m)	B.toe	8.19	5.36
Bank width (m)	B.all	26.36	7.08
Wall height (m)	H.wal	1.19	0.69

A response surface (RS) is a function which gives the safety factor by a function of the controlling parameters. It is important for a RS to distinguish between the safe region and the failure region. Thus the accuracy of RS near Fs=1 is important. A RS is obtained by regression analysis, thus many combinations of controlling parameters that give Fs near 1.0 are required.

A procedure to obtain a RS is follows:

Step 1: By applying the experimental design procedure, sensitivity of the parameters are evaluated (Shuku et al., 2014). Every parameter is set to have 2 levels, namely the mean and the mean plus or minus one s.d. Since the 7 parameters are introduced, $L_{7+1}(2^7)$ orthogonal table is employed which asks 9 combinations of the stability calculation. As a result, 6 parameters, namely ϕ', ke/kb, α.toe, α.hyd, H.wal and B.toe, are found to be more sensitive, which are taken into analysis in the next step for the cross effects. B.all has little sensitivity, and discarded from the further analysis.

Step 2: The first 5 parameters are considered to check for the cross effects. 5 parameters are taken because it is a convenient number for the experimental design. In this study, the cross effect of every 2 parameter combination is considered. This makes it necessary to employ $L_{31+1}(2^{31})$ orthogonal table which requires 32 combinations of parameter for the stability calculation. In order to look at the effect of B.toe, 16 more cases are additionally calculated. The total number of parameter combinations in Step 2 is 48 cases.

Step 3: All the cases calculated in Step 1 and 2, whose total number is 57, are used to finally identify the RS. Stepwise regression analyses are done to seek for the better combinations of the explanatory variables. In addition to the coefficient of determination, AIC and t-values, physical interpretation and engineering judgement are used to come up with the final RS.

3.2. The Obtained RS

The RS is thus obtained as follows:

$$\begin{aligned}\hat{F}_s &= 1.382 + 0.066 \cdot \phi' - 0.030 \cdot ke/kb \\ &-0.161 \cdot \alpha.toe - 0.081 \cdot \alpha.hyd \\ &+0.027 \cdot \alpha.toe \cdot \alpha.hyd - 0.049 \cdot H.wal \\ &+0.044 \cdot \alpha.toe \cdot H.wal + 0.125 \cdot H.wal \cdot B.toe\end{aligned} \quad (1)$$

The coefficient of determination of this regression equation is 0.94, which is considered to give reasonably good fit to the data.

The following interpretation may be possible for each term:

- ϕ' : strength parameter,
- ke/kb , α .hyd : parameter to determine the phreatic surface
- α.toe, H.wal, α.toe × H.wal, H.wal × B.toe : configuration parameters

The explanatory valuables introduced in Eq.(1) is standardized, *i.e.* the variables are transformed by the mean and the s.d. as follows:

$$x_i' = \frac{x_i - \mu_{x_i}}{\sigma_{x_i}} \quad (2)$$

Therefore, every coefficient shows the sensitivity of Fs for one standard deviation of shift from the base value. This sensitivity is illustrated in **Figure 6**.

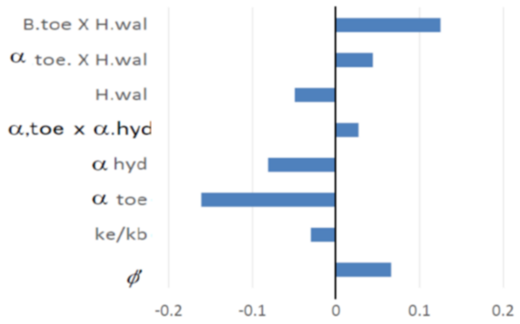


Figure 6 Sensitivity of parameters in the RS

It is important to notice that the geometrical parameters, such as α.toe, α.hyd, H.wal and B.toe, have much influence to Fs than the soil parameters, such as ϕ' and ke/kb for the shift of one s.d. from the base value. This fact implies that if one can get information on the configuration of levee; that would help the safety assessment considerably.

4. Continuous Safety Assessment of the Levee

4.1. Procedure and Statistics of the Input

As explained earlier, the detailed dimensions of levee section are known for every 200 m interval. The only uncertain variables in the RS function are soil parameters, namely ϕ' and ke/kb. Monte Carlo simulation (MCS) is done for every 200m of section by giving the section dimensions and generating the soil parameters based on the statistics given in **Table 3.** By using the RS, the probability of failure, *i.e.* the probability that Fs is equal to or below 1.0, can be estimated. 10,000 samples are generated at each section in the MCS.

Note that the estimated Pf is not the absolute value of the levee Pf because uncertainties in the high water level is not taken into account. The probability evaluated is a conditional failure probability given the high water level.

The steady state seepage analysis is also another conservative assumption because the

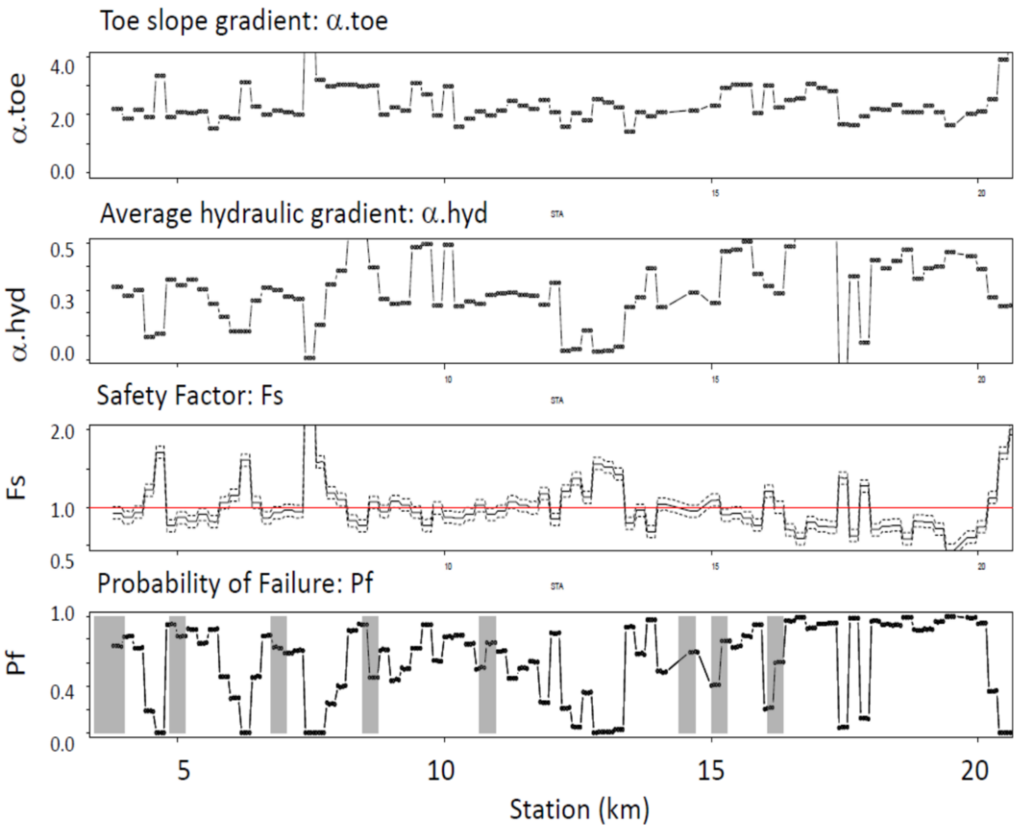


Figure 7 Continuous safety assessment of the levee (left bank)

duration of flood in Japan is usually not long enough to come to the steady state of the seepage flow in the levee.

4.2. Results of the assessment

The result of the assessment is presented in **Figure 7**. The upper two figures show the values of two most influential factors, α.toe and α.hyd, along 20 km stretch of the levee. In the third figure, the fluctuation of Fs, where the mean value and the mean $\pm$ s,d, range is presented.

Pf is given in the last row, and values are not low in the various part of levee. The reasons for these high Pf have been given already in the previous section. However, the priority for the reinforcement can be given for the higher Pf section. The gray color zones indicate the portion with past seepage damage records, which match with high Pf part to some extent.

5. Conclusions

A procedure to continuously assess safety of levee for seepage failure is proposed. The procedure is believed to give a solution for the problem raised in Honjo et al. (2015).

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