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Seismic Risk Management of a Canal System Model

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Abstract. This paper proposes a seismic risk management scheme for long continuous geotechnical structure, such as road embankment, water canal and so on. In this scheme, the continuous variation of responses, the failure probability and the risk, 50m intervals for instance, of the structure can be estimated with using response surface method. The detail of the proposed scheme and its applicability to the seismic risk management of continuous geotechnical structures are described from an application example to a more complex canal system model in this paper.

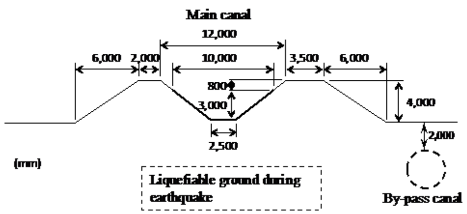
Keywords. Seismic risk management, long continuous structure, canal system, FE analysis, Monte Carlo Simulation

1. Introduction

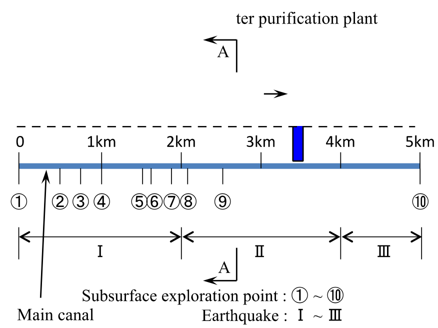
A canal system supplying drinking, industrial and aglicultural waters is one of the important infrastructures. Meanwhile, the occurrence of several large earthquakes has been a concern throughout Japan. Hence, early execution of countermeasures to achieve seismic disaster prevention of the systems is required. However, because of the limited seismic investment, the reasonable seismic disaster prevention of the canal systems has to be acheived. Under the circumstances, the development of a seismic risk management scheme to evaluate the priority of the countermeasures and the structures of the system is necessary to achieve reasonable seismic disaster prevention of the canal systems. For such purpose, the authors have conducted a study on the development of a scheme. In this paper, the detail of the proposed scheme and its applicability are introduced with an application example to a more complex canal system model.

2. Canal model

Figure 1 shows the 5km canal model supplying drinking, industrial and agricultural waters, which is adopted as an application example to evaluate the risk using the proposed scheme. The canal consists of a main canal of embankment, ($20m^3/s$), a siphone by-pass canal (steel pipe, STW400, ϕ = 2.2m, t = 11mm, $5.3m^3/s$), and a flow equalizing reservoir dam, (volume of 5 billion m^3).



(a) A-A section.

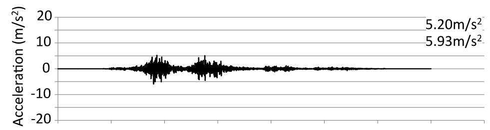


(b) Bird view.

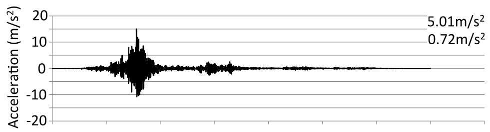
Figure 1. Canal model.

Drinking water ($1.182m^3/s$), and industrial water ($1.453m^3/s$), are supplied to a water purification plant at the 3.5km point of the canal.

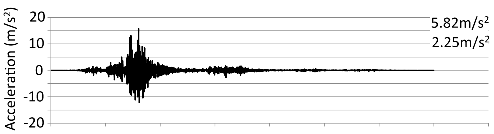
Agricultural water is supplied to the adjacent fields uniformly. Ten existing subsurface explorations and three target earthquake waves are assumed. Figure 2 shows the respective earthquake waves. Because of paper length limitaition, each result of the subsurface exploration with the Standard Penetration Test (SPT) is ommitted. In each boring point, N value measures are taken with one meter interval.



(a) Earthquake wave I



(b) Earthquake wave II



(c) Earthquake wave III

Figure 2. Earthquake waves for verification.

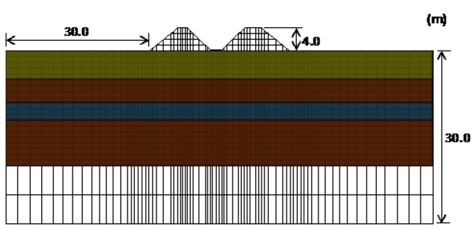


Figure 3. FEM mesh (LIQCA).

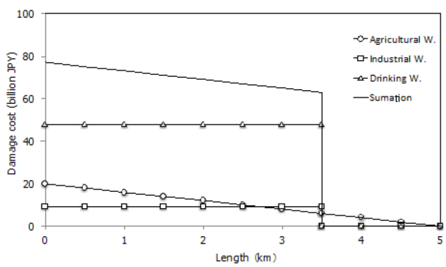


Figure 4. Damage cost.

The seismic responses of both main and by-pass canals are estimated by dynamic effective stress FEM (Oka et al. 1994), because the canals are built on or embedded in liquefiable ground during the earthquake. Figure 3 shows an example of FEM mesh based on one boring result.

Figure 4 shows the assumed damage cost of the waters at each point of the canal. Recovery term of drinking and industrial water supplies are assumed as two and four weeks, respectively.

3. Risk of the Main Canal Only

3.1. Risk Estimation Procedure

The scheme in Figure 5 shows the proposed risk estimation procedure. In this section, risk of the case with only main canal is estimated along the procedure.

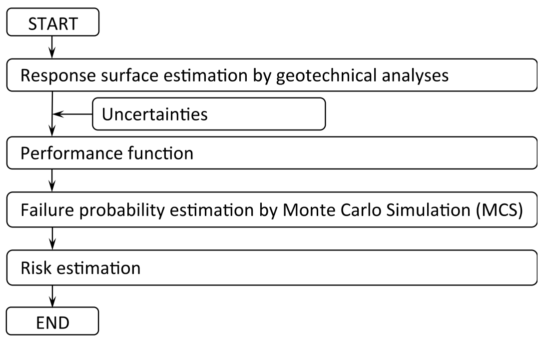


Figure 5. Risk estimation procedure.

3.2. Response Surface Estimation

Caluculation of several FEM cases for reliability analysis, such as one million times, is unreal, so response surface method (Honjo 2011) is adopted in the proposed scheme. Response surface means an approximate relationship between the responses estimated by FEM and contributable factors to the responses. The contributable factors in this response surface to estimate the responses obtained by FEM are only two, H_a and FS_{03}. Eqs. (1) and (2) are the response surface of the main canal, which are obtained from the relationship of H_a and FEM subsidences with respect to a specific earthquake, as shown in Figure 6, and the relationship of FS_{03} and FEM subsidences with respect to a specific ground condition, as shown in Figure 7. If a response surface could be established, one does not have to perform so many FEM calculations to perform a reliability analysis. However, the reproducibility of the response surface with respect to the responses estimated by FEM, as shown in Figure 8, has to be considered in the reliability analysis as one of the uncertainties, as shown in Eqs. (9) and (10).

$$S = \left[5.15 - 6.44\left\{1 - EXP\left(-\left[\frac{H_a - 0.6}{0.3}\right]^{0.14}\right)\right\}\right] \left[1 - EXP\left(-\left[\frac{FS_{03} - 1.8}{1.8}\right]^{0.7}\right)\right], \quad (0.62 < H_a) \qquad (1)$$

$$S = 3.67\left[1 - EXP\left(-\left[\frac{0.7 - H_a}{0.3}\right]^{0.13}\right)\right] \left[1 - EXP\left(-\left[\frac{FS_{03} - 1.8}{1.8}\right]^{0.7}\right)\right], \quad (H_a \leq 0.62) \qquad (2)$$

where, S = subsidence (m), H_a = mean shear stiffness of the ground within 20m from the surface (10^5 kPa), which is calculated by Eq. (3), a = correction coefficient concerning depth of liquefiable layer from the surface, which is presented by Eq. (4), with maximum value of a of 1.0, x = depth from the ground surface (m), F_L = resistance ratio against liquefaction (Tatsuoka et al. 1982), which is calculated by Eq. (5), R = liquefaction strength ratio, L = cyclic shear stress ratio during earthquake, G_{N1} = shear modulus (kPa), which is calculated by Eq. (6), γ_t = wet unit weight of soil (kN/m^3), g = gravitational acceleration (m/s^2), V_{sN1} = shear wave velocity (m/s), which is calculated by Eq. (7), N_1 = revised SPT-N value by confining pressure, which is calculated by Eq. (8), N = SPT-N value, σ_v' = effective confining pressure (kPa), FS_{03} = integral acceleration Fourier spectra of 0 – 3Hz (10^2m/s^2), FS_{03} of earthquake I, II and III are 2.94, 5.00, 10.1, respectively.

$$H_a = \sum_{0}^{20} a \cdot G_{N1} \cdot F_L^2 \cdot dx \Big/ 20 \qquad (3)$$

$$a = 1.0 \quad (F_L \geq 1.0), \; a = 0.1x \; (F_L < 1.0) \qquad (4)$$

$$F_L = R/L \qquad (5)$$

$$G_{N1} = \frac{\gamma_t}{g} \cdot V_{sN1} \qquad (6)$$

$$V_{sN1} = 80 \cdot N_1^{1/3} \qquad (7)$$

$$N_1 = \frac{170N}{\sigma_v' + 70} \qquad (8)$$

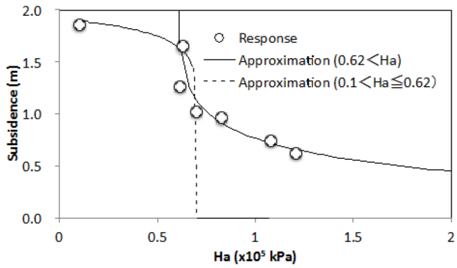


Figure 6. Relationship of H_a and FEM responses.

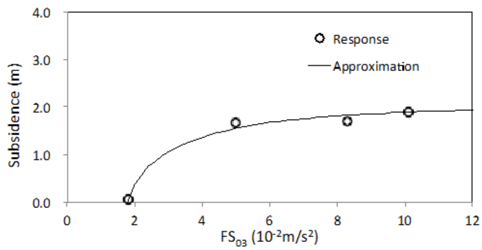


Figure 7. Relationship of FS_{03} and FEM responses.

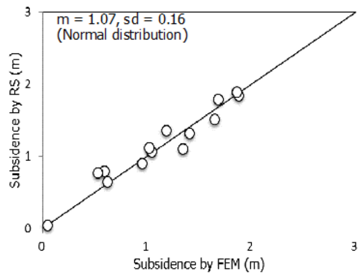


Figure 8. Reproducibility of response surface.

3.3. Uncertainties

Figure 9 shows the reproducibility of FEM adopted in this example, which was obtained from blind tests on an embankment built on liquefied ground during earthquake (JICE 2002), by comparing between experimental results and FEM ones. Because of blind testing, setting error of geotechnical parameters input to FEM are included in this uncertainty. Figure 10 shows the variation of H_a value obtained by previous 10 borings, which is estimated by Kriging method (Dagan 1982: Otake and Honjo 2012) with an autocorrelation distance of 200m. This variation expresses the uncertainty to apply to the investigation data in other areas, where investigation is not carried out. H_a value at each investigation point was treated as deterministic value in this example.

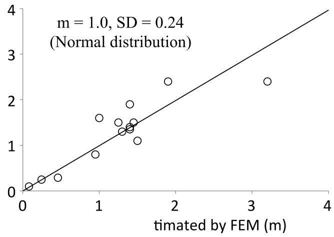


Figure 9. FEM reproducibility.

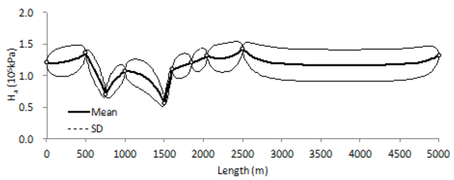


Figure 10. FEM reproducibility.

3.4. Failure Probability Estimation

Eqs. (9) and (10) present the performance functions in order to estimate the failure probability. The limit state of the embankment is defined as a subsidence value of 1.2m, and the seismic response of the embankment is estimated by the response surface.

$$(0.62 < H_a)$$
$$S = R - S$$
$$= 1.2 - \left[5.15 - 6.44\left\{1 - EXP\left(-\left[\frac{H_a \cdot \delta_{Ha} - 0.6}{0.3}\right]^{0.14}\right)\right\}\right] \cdot \left[1 - EXP\left(-\left[\frac{FS_{03} - 1.8}{1.8}\right]^{0.7}\right)\right] \cdot \delta_{RS} \cdot \delta_{FEM} \geq 0 \quad (9)$$

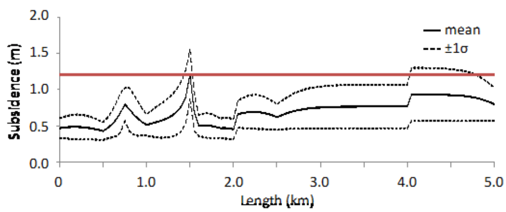
$$(H_a \leq 0.62)$$
$$S = R - S$$
$$= 1.2 - 3.67\left[1 - EXP\left(-\left[\frac{0.7 - H_a \cdot \delta_{Ha}}{0.3}\right]^{0.13}\right)\right] \cdot \left[1 - EXP\left(-\left[\frac{FS_{03} - 1.8}{1.8}\right]^{0.7}\right)\right] \cdot \delta_{RS} \cdot \delta_{FEM} \geq 0 \quad (10)$$

Here, δ_{Ha}, δ_{RS}, δ_{FEM} are uncertainties, random variables, respectively of H_a value, of the response surface reproducibility of the response estimated by FEM, and of the FEM reproducibility of the experimental results, as presented on Table 1.

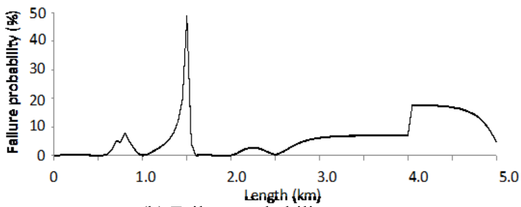
The failure probability was estimated by Monte Carlo method with one million simulations, and the probability is estimated by 50m intervals of the canal embankment model. The variation of subsidence and the failure probability at each point of the embankment canal model are shown in Figure 11.

Table 1. Random variables of Eqs (9) and (10).

	Content	Random variable		Distro
		Mean	S.D.	
δ_{Ha}	Variation of H_a	Variation at given point		Normal
δ_{RS}	Reproducibility of response surface	1.07	0.16	Normal
δ_{FEM}	Reproducibility of FEM	1.00	0.24	Normal



(a) Subsidence.



(b) Failure probability.

Figure 11. Subsidence and failure probability.

3.5. Risk Estimation

The risk at a given point is estimated by the product of soundness probability of upstream canal from the given point, the failure probability and the damage cost at the given point, as presented by Eq. (11), and the entire risk is estimated by Eq. (12). Figure 12 shows the risk distribution in the case without countermeasures and the entire risk is estimated as 67.6 billion JPY.

$$R_i=(1-p_1)\cdot(1-p_2)\cdots(1-p_{i-1})\cdot p_i\cdot D_i \quad (11)$$

$$R=\sum_{i=1}^{n}R_i \quad (12)$$

where, R_i = Risk on No.i point, P_i = Failure probability on No.i point, D_i = Damage cost on No.i point. Here, the length of each point is 50m.

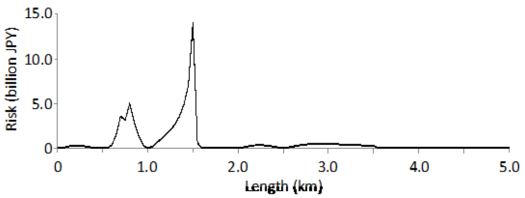


Figure 12. Risk estimation.

4. Risk of the Main and By-Pass Canals

4.1. Response Surface of the By-Pass Canal

Because the by-pass canal is steel siphone pipe, the maximum stress occurring in its section is focused on in order to establish response surface. Eqs. (13) and (14) are the response surface of the amplification ratio of the maximum stress from the initial one before earthquake for the siphone pipe canal, which are obtained from the relationship of the contributable factors, thickness of the liquefiable layer embedded the pipe, FS_{03}, as shown in Figures 13 and 14.

$(0\le T_L\le 4.0)$

$$\Delta\sigma_{0max}=\left[7+22\left\{1-EXP\left(-\left[\frac{T_L}{1.8}\right]^{0.8}\right)\right\}\right]\cdot\left[0.032+1.08\left\{1-EXP\left(-\left[\frac{FS_{03}}{2.5}\right]^{1.4}\right)\right\}\right] \quad (13)$$

$(4.0<T_L)$

$$\Delta\sigma_{0max}=\left[26-12\left\{1-EXP\left(-\left[\frac{T_L-4}{0.4}\right]^{0.9}\right)\right\}\right]\cdot\left[0.032+1.08\left\{1-EXP\left(-\left[\frac{FS_{03}}{2.5}\right]^{1.4}\right)\right\}\right] \quad (14)$$

where, $\Delta\sigma_{0max}$ = amplification ratio of the maximum stress occuring in the pipe section during earthquake from the initial one before earthquake, T_L = thickness of the liquefiable layer embedded the pipe.

Figure 15 shows the response surface reproducibility of FEM results.

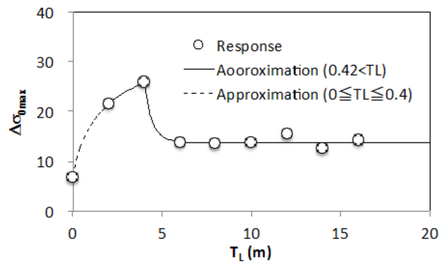


Figure 13. Relationship of T_L and FEM responses.

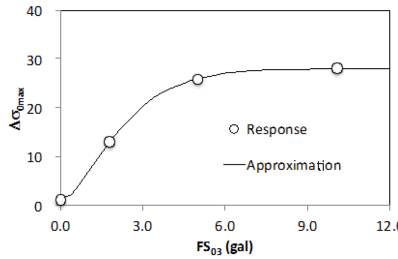


Figure 14. Relationship of FS_{03} and FEM responses.

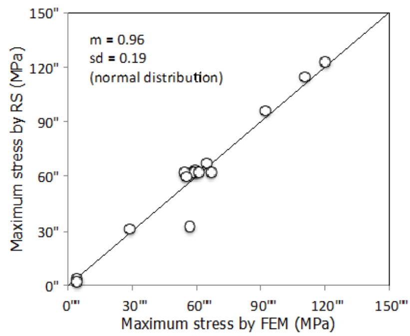


Figure 15. Reproducibility of response surface.

4.2. Failure Probability and Risk

The variation of yeild stress and thickness of the by-pass pipe is assumed as m = 1.67, sd = 0.12, and m = 1.0, sd = 0.033, respectively. The failure probability occurring simultaneously in both main canal and by-pass canal is estimated from the variation of H_a, T_L and FS_{03} at each point, as shown in Figure 16. Figure 17 shows the risk distribution in the case of both canals. The residual risk can be reduced to 11.8 billion JPY from one of the case with main canal only, 67.6 billion JPY. According to the result, the effectiveness of by-pass canal as seismic countermeature is large. Here, a remaining risk is the agricultural water supply, which the by-pass canal cannot cover from its supply water volume.

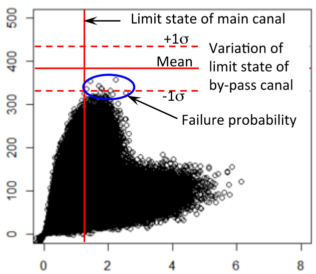


Figure 16. Failure robability consideration.

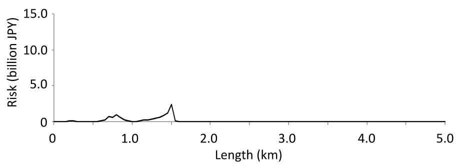


Figure 17. Risk distribution of main and by-pass canal.

5. Risk of the Main Canal and the Reservoir Dam and All Facilities

The limit state of the reservoir dam is defined in terms of subsidence, with a limit of 2.0m. The seismic response of the dam was estimated as 1.77m from a FEM analysis. Figure 18 shows the risk distribution in the case of both the main canal and the target dam. Here, FEM reproducibility is adopted as the seismic response variation of the dam. The residual risk can be reduced to 26.3 billion JPY from one of the case with main canal only, 67.6 billion JPY. According to the rsult, the effectiveness of dam as seismic countermeasure is also large.

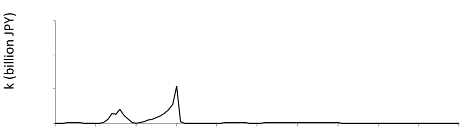


Figure 18. Risk distribution of main canal and dam.

Figure 19 shows the risk distribution in the case of all facilities, the main and by-pass canals and the reservoir dam. The residual risk can be reduced to 10.7 billion JPY. According to the result, the risk distribution of Figure 19 is very similar to the one presented in Figure 17, this means that the effectiveness of a dam as a seismic countermeasure is not so large as after the completion of the by-pass canal.

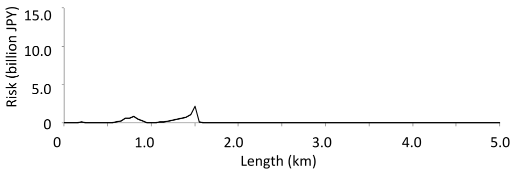


Figure 19. Risk distribution of all structures.

6. Conclusions

The continuous variation of seismic responses, failure probabilities and risk of each canal as well as the distributions depending on the respective combinations of the facilities can be estimated by the proposed scheme. The results mean that the proposed scheme can contribute to achievement of reasonable seismic disaster prevention.

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