Design Code for Agricultural Canals Based on Partial Safety Factors

S. Nishimura[1]

[1]Graduate School of Environmental and Life Science, 3-1-1 Tsushima-naka, Kita-ku, Okayama 700-8530, Japan.
E-mail: theg1786@okayama-u.ac.jp

Abstract: Japanese design codes are moving to the performance-based design. For the agricultural facilities, the trend is same. The author discusses the limit state design of the agricultural canal. The canals have very long lengths and one of the main facilities for the agricultural water supply system. Here, in this study, the limit state design approach is applied to the canal design based on the partial safety factor approach. Firstly, the variability, of the soil parameters are determined. The internal friction angle, unit weight and cohesion are variable soil parameters. Secondly, the FORM-based reliability analysis is conducted, and the reliability index is calculated for the several canal sites. Finally, the partial safety factors are determined for each parameters. In conclusion, the possibility of the limit state design has been confirmed.

Keywords: Agricultural canal; limit state design; partial safety factor; reliability index; reliability analysis; FORM.

1 Introduction

The Japanese Geotechnical Society (JGS) published the Japanese Geotechnical Standard, i.e., JGS4001-2004, entitled 'Principles for Foundation Designs Grounded on a Performance-based Design Concept' (JGS 2004) to introduce a performance-based design for foundation structures, and developed a design code for geotechnical structures. For the agricultural facilities, the performance-based design was introduced (Japan Society of Irrigation, Drainage and Reclamation Engineering 2008). In this standard, the limit state design is introduced into their design criteria. In the agricultural design codes, the performance-based design concept based on the limit state design begins to be introduced. In the current design code of the agricultural open channels (Ministry of Agriculture, Forestry, and Fishery, Rural Development Bureau 2014), the limit state design concept is introduced for the concrete structures. While, Murakami et al. (2011) presented the limit state design concept for the foundation design of the open channels, and the contents are summarized in this paper.

A modified Terzaghi's bearing capacity formula is employed as an evaluation method for the bearing capacity. The shear strength parameters, cohesion c and internal friction angle ϕ, and soil density γ are dealt with as probabilistic parameters, while the load due to self weights of the concrete structure of the channel and the inside water, is considered as a static and deterministic parameter, since the impact of the load is relatively small for the design of open channels. The statistical moments of the soil parameters are determined from the published data records.

Firstly, the reliability analyses are performed for sixteen open channels in Japan, and the reliability indices are presented. The partial factors to satisfy the target reliability indices are then determined for existing open channels. The determined partial factors for cohesion c, internal friction angle ϕ, and soil density γ are averaged for sixteen cases. As the target reliability indices, β_t = 2.0, 3.0, and 4.0 are herein adopted.

2 Reliability Analysis for Open Channels

2.1 Formulation of reliability index

Most modern bearing capacity predictions involve a relationship of the form (Terzaghi 1943)

$$q_u = c \cdot N_c + \frac{1}{2}\gamma_1 \cdot B \cdot \eta \cdot N_\gamma + \gamma_2 \cdot D_f \cdot N_q \tag{1}$$

where c is the cohesion of the soil below the foundation (kPa); γ_1 is the unit weight of the soil below the foundation (kN/m^3); γ_2 is the unit weight of the soil in the embedment portion (kN/m^3); N_c, N_γ, and N_q are the coefficients of the bearing capacity; D_f is the embedment depth of the foundation (m); B is the length of the foundation's shorter side (m); η is the correction factor due to the scale effect of the foundation.

$$\begin{cases} N_c = \left(N_q - 1\right)\cot\phi & (\phi \neq 0) \\ N_c = 5.14 & (\phi = 0) \end{cases} \tag{2}$$

Proceedings of the 7th International Symposium on Geotechnical Safety and Risk (ISGSR)
Editors: Jianye Ching, Dian-Qing Li and Jie Zhang

Published by Research Publishing, Singapore.
ISBN: 978-981-11-2725-0; doi:10.3850/978-981-11-2725-0_MS1-3-cd

$$N_q = \frac{1+\sin\phi}{1-\sin\phi}\exp(\pi\cdot\tan\phi) \tag{3}$$

$$N_\gamma = (N_q - 1)\tan(1.4\phi) \tag{4}$$

The performance function is defined using the following equations.

$$g_q = q_u(c,\phi,\gamma_1,\gamma_2) - q_{\max} \tag{5}$$

where $q_{\max}$ is the maximum loading stress due to self weights of the concrete structure, of the channel, and the inside water, which is treated as a deterministic variable. The probabilistic variables for analysis are: c, $\mu = \tan\phi$, γ_1, and γ_2. The definitions of variables are presented in Figure 1. Because the loading stress $q_{\max}$ is different in each case appeared in Table 1 and greatly variable, the maximum and deterministic value, $q_{\max}$ is employed as a load factor for the safety side design.

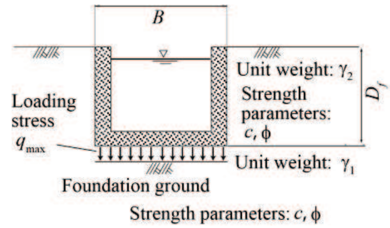

Figure 1. Definition of variables of an open channel in Eq.(1).

The Taylor series expansion of the performance function at design points, e.g., $(c^*, \mu^*, \gamma_1^*, \gamma_2^*)$, is obtained as

$$\hat{g}_q = \left.\frac{\partial g_q}{\partial c}\right|_{c=c^*}(c-c^*) + \left.\frac{\partial g_q}{\partial \mu}\right|_{\mu=\mu^*}(\mu-\mu^*) + \left.\frac{\partial g_q}{\partial \gamma_1}\right|_{\gamma_1=\gamma_1^*}(\gamma_1-\gamma_1^*) + \left.\frac{\partial g_q}{\partial \gamma_2}\right|_{\gamma_2=\gamma_2^*}(\gamma_2-\gamma_2^*) \tag{6}$$

$$\frac{\partial g_q}{\partial c} = N_c \tag{7}$$

$$\frac{\partial g_q}{\partial \mu} = c\frac{\partial N_c}{\partial \mu} + \frac{1}{2}\gamma_1\cdot B\cdot\eta\cdot\frac{\partial N_\gamma}{\partial \mu} + \gamma_2\cdot D_f\frac{\partial N_q}{\partial \mu} \tag{8}$$

$$\frac{\partial g_q}{\partial \gamma_1} = \frac{1}{2}B\cdot\eta\cdot N_\gamma \tag{9}$$

$$\frac{\partial g_q}{\partial \gamma_2} = D_f\cdot N_q \tag{10}$$

Four probabilistic variables are normalized as defined in the following equation and have a normal distribution of $N(0,1)$ when c, μ, γ_1, and γ_2 follow the normal distribution:

$$X_c = \frac{c-m_c}{\sigma_c},\ X_\mu = \frac{\mu-m_\mu}{\sigma_\mu},\ X_{\gamma_1} = \frac{\gamma_1-m_{\gamma_1}}{\sigma_{\gamma_1}},\ X_{\gamma_2} = \frac{\gamma_2-m_{\gamma_2}}{\sigma_{\gamma_2}} \tag{11}$$

The following definitions are also used at design points (c^*, μ^*, γ_1^*, and γ_2^*):

$$X_c^* = \frac{c^*-m_c}{\sigma_c},\ X_\mu^* = \frac{\mu^*-m_\mu}{\sigma_\varphi}, X_{\gamma_1}^* = \frac{\gamma_1^*-m_{\gamma_1}}{\sigma_{\gamma_1}}, X_{\gamma_2}^* = \frac{\gamma_2^*-m_{\gamma_2}}{\sigma_{\gamma_2}} \tag{12}$$

where m_c, m_μ, $m_{\gamma1}$, and $m_{\gamma2}$ are the averages for c, μ, γ_1, and γ_2; σ_c, σ_μ, $\sigma_{\gamma1}$, and $\sigma_{\gamma2}$ are the standard deviations for c, c, μ, γ_1, and γ_2. The derivative of the performance function should satisfy the following equation from Eq. (11):

$$\frac{\partial g_q}{\partial c} = \frac{1}{\sigma_c}\frac{\partial g_q}{\partial X_c},\ \frac{\partial g_q}{\partial \mu} = \frac{1}{\sigma_\mu}\frac{\partial g_q}{\partial X_\mu},\ \frac{\partial g_q}{\partial \gamma_1} = \frac{1}{\sigma_{\gamma_1}}\frac{\partial g_q}{\partial X_{\gamma_1}},\ \frac{\partial g_q}{\partial \gamma_2} = \frac{1}{\sigma_{\gamma_2}}\frac{\partial g_q}{\partial X_{\gamma_2}} \tag{13}$$

The expected value of the performance function is approximated with Eq. (14) derived from Eq.(6) as

$$\begin{aligned} m_g &= \left.\frac{\partial g_q}{\partial c}\right|_{c=c^*}(m_c-c^*) + \left.\frac{\partial g_q}{\partial \mu}\right|_{\phi=\phi^*}(m_\mu-\mu^*) + \left.\frac{\partial g_q}{\partial \gamma_1}\right|_{\gamma_1=\gamma_1^*}(m_{\gamma_1}-\gamma_1^*) + \left.\frac{\partial g_q}{\partial \gamma_2}\right|_{\gamma_2=\gamma_2^*}(m_{\gamma_2}-\gamma_2^*) \\ &= -\left.\frac{\partial g_q}{\partial X_c}\right|_{c=c^*}X_c^* - \left.\frac{\partial g_q}{\partial X_\mu}\right|_{\mu=\mu^*}X_\phi^* - \left.\frac{\partial g_q}{\partial X_{\gamma_1}}\right|_{\gamma_1=\gamma_1^*}X_{\gamma_1}^* - \left.\frac{\partial g_q}{\partial X_{\gamma_2}}\right|_{\gamma_2=\gamma_2^*}X_{\gamma_2}^* \end{aligned} \tag{14}$$

The standard deviation of the performance function is written in Eq. (15) as

$$\sigma_g = \left\{ \left(\frac{\partial g_q}{\partial c}\Big|_{c=c^*} \right)^2 \sigma_c^2 + \left(\frac{\partial g_q}{\partial \mu}\Big|_{\mu=\mu^*} \right)^2 \sigma_\mu^2 + \left(\frac{\partial g_q}{\partial \gamma_1}\Big|_{\gamma_1=\gamma_1^*} \right)^2 \sigma_{\gamma_1}^2 + \left(\frac{\partial g_q}{\partial \gamma_2}\Big|_{\gamma_2=\gamma_2^*} \right)^2 \sigma_{\gamma_2}^2 \right\}^{1/2}$$
$$= \left\{ \left(\frac{\partial g_q}{\partial X_c}\Big|_{c=c^*} \right)^2 + \left(\frac{\partial g_q}{\partial X_\mu}\Big|_{\mu=\mu^*} \right)^2 + \left(\frac{\partial g_q}{\partial X_{\gamma_1}}\Big|_{\gamma_1=\gamma_1^*} \right)^2 + \left(\frac{\partial g_q}{\partial X_{\gamma_2}}\Big|_{\gamma_2=\gamma_2^*} \right)^2 \right\}^{1/2} \tag{15}$$

The reliability index is computed using the average and the standard deviation from Eq. (16).

$$\beta = \frac{\mu_g}{\sigma_g} = -\frac{1}{\sigma_g} \left(\frac{\partial g_q}{\partial X_c}\Big|_{c=c^*} X_c^* + \frac{\partial g_q}{\partial X_\mu}\Big|_{\mu=\mu^*} X_\phi^* + \frac{\partial g_q}{\partial X_{\gamma_1}}\Big|_{\gamma_1=\gamma_1^*} X_{\gamma_1}^* + \frac{\partial g_q}{\partial X_{\gamma_2}}\Big|_{\gamma_2=\gamma_2^*} X_{\gamma_2}^* \right)$$
$$= -\alpha_c X_c^* - \alpha_\mu X_\mu^* - \alpha_{\gamma_1} X_{\gamma_1}^* - \alpha_{\gamma_2} X_{\gamma_2}^* \tag{16}$$

where α_c, α_μ, $\alpha_{\gamma 1}$, and $\alpha_{\gamma 2}$ are called the sensitivity and are defined as follows:

$$\alpha_c = \frac{1}{\sigma_g}\left(\frac{\partial g_q}{\partial X_c}\Big|_{c=c^*} \right), \alpha_\mu = \frac{1}{\sigma_g}\left(\frac{\partial g_q}{\partial X_\mu}\Big|_{\mu=\mu^*} \right), \alpha_{\gamma_1} = \frac{1}{\sigma_g}\left(\frac{\partial g_q}{\partial X_{\gamma_1}}\Big|_{\gamma_1=\gamma_1^*} \right), \alpha_{\gamma_2} = \frac{1}{\sigma_g}\left(\frac{\partial g_q}{\partial X_{\gamma_2}}\Big|_{\gamma_2=\gamma_2^*} \right) \tag{17}$$

2.2 Statistics of parameters

The statistical values of soil parameters, e.g., c, $\mu = \tan\phi$, γ_1, and γ_2 are obtained by collecting data from the references, for example, Matsuo (1984) and JGS (1988). The internal friction angles are determined from the tests of sand materials as the effective internal friction angle ϕ', and the cohesions are determined from clays as the undrained shear strength, c_u. The following coefficients of variation for different variables are adopted for subsequent analyses.

Unit weight, γ_1 and γ_2: 0.06; Coefficient of friction, $\mu = \tan\phi$: 0.15; Cohesion, c: 0.30

Table 1. Profiles of the open channels.

#	Width B of open channel (m)	Height H of open channels (m)	Soil type*	Unit weight (kN/m³)	Strength parameter c_u (kPa),	Strength parameter ϕ' (°)	Loading stress q_{max} (kPa)
1	2.96	1.62	S	19.8	0	35	22
2	3.00	1.80	S	18.0	0	23	27
3	2.32	1.20	C	14.0	13	0	21
4	1.70	0.90	C	19.8	18	0	19
5	1.90	1.65	S	20.0	0	25	25
6	2.00	1.70	S	20.0	0	25	33
7	2.00	1.20	S	20.0	0	25	13
8	4.50	1.80	S	19.8	0	23	22
9	2.85	1.65	S	18.8	0	29	24
10	7.90	2.48	S	20.0	0	25	37
11	2.80	1.00	S	20.0	0	25	15
12	2.00	2.20	S	20.0	0	30	21
13	3.30	1.80	S	18.0	0	15	23
14	3.30	1.80	C	15.0	8.0	0	23
15	3.40	1.00	S	20.0	0	20	16
16	2.20	1.20	S	20.0	0	20	16

*S: Sand, C: Clay

Maximum bearing stress, q_{max}, is treated as being static and deterministic. Since the expected value of q_{max} is relatively small in this problem, compared with the q_u value, the variability of this quantity does not significantly affect the results of the computation.

2.3 Reliability analysis and discussion

Table 1 lists the dimensions of sixteen open channels and the average strength parameters and load. The sixteen cases cover thirteen cases for sandy soil under the condition of $c=c_u=0$ and three cases for clayey soil under the condition of $\phi=\phi'=0$. The unit weight considering the buoyancy force below the water level is adopted for the computation.

Table 2 shows the reliability indices and sensitivities for each soil parameter for the sixteen cases studied. It is revealed that the reliability indices for sandy soil are between 5.2 and 17.6, in which the reliability indices and sensitivities for each ground parameter are listed for the sixteen case studies. Since parameters N_q and N_γ in Eq. (1) are very sensitive to the internal friction angle and the maximum load q_{max} is relatively small compared to the value of q_u in the problems of the open channels, the value of the performance function becomes extremely large easily. In the cases of the clayey soil, friction angle ϕ is zero and the value of q_u has a linear relationship with cohesion c, namely, there is no extreme change in bearing capacity q_u for the change in c. Consequently, the reliability indices are very similar among three cases.

Table 2. Reliability indices and sensitivities of the soil parameters.

#	β	Soil type*	Sensitivity for parameters			
			c_u	μ =tanϕ'	γ_1	γ_2
1	11.0	S	—	0.985	0.000	0.171
2	6.1	S	—	0.963	0.003	0.268
3	3.2	C	0.997	—	0.000	0.071
4	3.2	C	0.999	—	0.000	0.041
5	10.0	S	—	0.963	0.000	0.268
6	5.9	S	—	0.975	0.003	0.224
7	12.7	S	—	0.956	0.000	0.294
8	5.2	S	—	0.988	0.016	0.154
9	17.0	S	—	0.986	0.000	0.167
10	7.5	S	—	0.968	0.000	0.251
11	9.5	S	—	0.963	0.000	0.271
12	17.6	S	—	0.961	0.000	0.275
13	6.5	S	—	0.887	0.003	0.462
14	2.9	C	0.990	—	0.000	0.140
15	6.3	S	—	0.957	0.003	0.290
16	14.0	S	—	0.838	0.000	0.545

*S: Sand, C: Clay

The sensitivity of the internal friction angle is dominant for the sandy grounds, and cohesion c has dominant sensitivity for the clayey grounds. The unit weights, γ_1 and γ_2, have small sensitivities. Since unit weight $\gamma_1$is usually treated as a submerged unit weight, the sensitivity to the bearing capacity is smaller than for unit weight γ_2.

Consequently, the reliability indices are greater than 5.0 for the sandy grounds. Although the reliability indices for the clayey grounds are almost 3.0, which sounds like a small value, the corresponding probability of failure is 0.1%, and thus, the structures on the ground are sufficiently safe..

3 Determination of Partial Factors for the Foundation of Open Channels

3.1 Determination of partial factors

When probabilistic variables for the ground parameters follow a normal distribution and their characteristic value is the average, partial factor ρ is defined as follows:

$$\rho = f_k / f_d = 1/\left(1 - V\alpha\beta_t\right) \tag{18}$$

where f_k is the characteristic value for the parameter, usually, $f_k = m$; f_d is the design value for the parameter, for the reliability analysis; V is the coefficient of the variation in the parameter; α is the sensitivity of the parameter; β_t is the target reliability index.

When probabilistic variables follow a logarithmic normal distribution, partial factor ρ is written as the following equation:

$$\rho = f_k / f_d \tag{19}$$

where λ is the average normal logarithm for probabilistic variables, $\lambda = \ln\left(m/\sqrt{1+V^2}\right)$; ζ is the standard deviation of the normal logarithm for probabilistic variables, $\zeta = \sqrt{\ln\left(1+V^2\right)}$; m is the average of the probabilistic variables.

In the reliability analysis in this section, ratio of internal friction angle $\mu=\tan\phi'$ follows the normal distribution, while the undrained shear strength c_u is assumed to be lognormally distributed. The coefficient of variation for c_u was assumed to be 0.3, which is large in terms of reliability theory but appropriate for c_u, as a result the partial factor could not be defined to achieve $\beta_t = 4.0$.

Table 3. Expected values of sensitivities for sixteen cases β_t

Target reliability index β_t	Expected value of sensitivity α					
	Sand			Clay		
	μ=tanϕ'	γ_1	γ_2	c_u	γ_1	γ_2
β_t=2	0.981	0.047	0.179	0.984	0.000	0.160
β_t=3	0.979	0.035	0.189	0.974	0.000	0.208
β_t=4	0.977	0.023	0.201	0.958	0.000	0.263

Table 4. Mean values of partial factors for sixteen cases.

Target reliability index β_t	Mean values of partial factor, ρ					
	Sandy soil			Clayey soil		
	μ=tanϕ'	γ_1	γ_2	c_u	γ_1	γ_2
β_t=2	1.42	1.01	1.02	1.86	1.00	1.02
β_t=3	1.79	1.01	1.03	2.46	1.00	1.04
β_t=4	2.42	1.01	1.05	3.22	1.00	1.07

3.2 Performance function for calibration analysis

Since the maximum load $q_{\max}$ values are relatively small as seen in Table 1, the calculated reliability indices have great values as shown in Table 2. The values of $q_{\max}$, however, are different for each site, and therefore, the actual $q_{\max}$ values are not used for the determination of the partial factors. As a performance function, Eq. (20) is employed in following sections instead of Eq. (5).

$$g_q = q_u - q_d \qquad (20)$$

where q_d is the design bearing capacity, and adjusted so that the computed reliability index based on the Eq.(20) exactly coincides with the target reliability index in the calibration analysis.

3.3 Computation of partial factors by design values

The partial factors for each case listed in Table 4 are computed for the target reliability indices of β_t=2, 3, and 4 based on Eqs. (18) and (19). Among the ground parameters, the partial factors for unit weight and coefficient of internal friction angle tanϕ are computed based on Eq. (18) by adopting the coefficients of the variation of 0.06 for both γ_1 and γ_2, and 0.15 for tanϕ under the assumption that their probability follows a normal distribution. As for cohesion, different partial factors for each case are evaluated by Eq. (19) depending on characteristic values, because cohesion c follows a logarithmic normal distribution.

In Tables 3, the expected values of the sensitivities calculated based on Eq. (17) are listed for the target reliability indices of β_t= 2, 3, and 4, respectively. According to the tables, the sensitivity values of the internal friction angle and the cohesion are greater than 0.95, while those of the unit weights γ_1 and γ_2 are less than 0.26. The results of Table 3 insist that the strength parameters are definitely high and dominant for the sensitivity. Table 4 shows a set of partial factors for each target reliability index, β_t. The partial factors for the strength parameters, c_u and tanϕ' are quite large, while the partial factors of unit weights γ_1 and γ_2 are comparatively small between 1.00 and 1.07.

4 Conclusions

This paper has evaluated reliability indices for the foundations of existing open channels in order to examine the safety of the current design method for the bearing capacity and the effect of the uncertainty of soil parameters. The concluding remarks are as follows.

1. The statistical properties of the soil parameters were investigated based on the published data and the results of tests conducted at several sites. The coefficients of variation have been determined to be 0.3, 0.15, and 0.06 for the cohesion, the internal friction angle, and the unit weight, respectively.
2. Reliability analyses have been performed for the sixteen sites designed with the current design code. Consequently, it has been revealed that the current code presents a conservative design for the bearing capacity of foundations with a reliability index greater than 3.0, and that the internal friction angle and the cohesion are the dominant parameters that affect the safety.
3. The reliability index obtained for sandy soil is greater than 5.0 in the sites of open channels constructed based on the conventional design code. The value of 5.0 is too conservative. The reliability index for clayey soil is approximately 3.0, which is smaller than that for sandy soil.
4. The partial factors have been obtained by considering the sensitivity of the variability in the soil parameters for three target reliability indices, namely, 2, 3, and 4. Finally, design partial factors corresponding to the target reliability indices have been proposed as the mean values for the sixteen cases.

The results obtained in the current paper are limited to shallow foundations under open channels, but the evaluation of the reliability indices shown herein is effective for any type of structure.

References

Japanese Geotechnical Society (1988). *Variability of Soil Data and Design* (in Japanese).

Japanese Geotechnical Society (2004). *JGS4001-2004: Principles for Foundation Designs Grounded on a Performance-Based Design Concept*.

Japan Society of Irrigation, Drainage and Reclamation Engineering (JSIDRE). (2008). *Introduction to Performance-Based Design for Functional Maintenance of Agricultural Facilities*, JSIDRE (in Japanese).

Matsuo, M. (1984). *Geotechnical Engineering –Theory and Practice of Reliability Theory*, Gihodo (in Japanese).

Ministry of Agriculture, Forestry, and Fishery, Rural Development Bureau (2014). *Design codes for the agricultural facilities – Design of agricultural canals–*, JSIDRE (in Japanese)

Murakami, A., Nishimura, S., Suzuki, M., Mori, M., Kurata, T., and Fujimura, T. (2011). Determination of partial factors for the verification of the bearing capacity of shallow foundations under open channels. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards,* 5(3-4), 186-194.