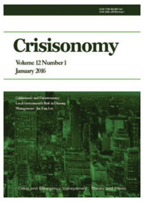

Crisisonomy Vol.12 No.10, 149-158
ISSN 2466-1198 (Print) ISSN 2466-1201 (Online) http://dx.doi.org/10.14251/crisisonomy.2016.12.10.149

Crisisonomy

Reliability Analysis of Embankment Reflecting Spatial Variability of Soil Parameters

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Abstract

The evaluation of embankment stability was performed based on the results from a conventional deterministic analysis and a reliability analysis. The embankment used in the analyses was selected from real sites located at Goryeong area in South Korea. The Bishop simplified method was implemented to calculate driving and resistance moments of the embankment. In the reliability-based design, Gaussian random field theory was used to account for spatial variabilities of soil properties. The results show that the calculated factors of safety (FS) from the conventional deterministic analyses exceeded the minimum FS proposed in design codes. Also, the random field-based reliability analyses revealed that the probability of embankment failure assuming no water table was much lower than the lower bound of the proposed target probability of failure. However, under increasing levels of water table, FS drops and the probability of failure increases significantly.

Key words: embankment, probability of failure, water table, Monte Carlo simulation

Ⅰ. INTRODUCTION

Embankments are generally constructed to be used as a substructure of roadway utilized for transportation purpose or prevention barrier against flooding of water ways, such as river, stream, or lake. Alternative terminology of the embankments constructed for the purpose of preventing embankment failure against flooding is levee. Unlikely to simple failures of roadway embankments that are not concerned with flooding, typically, their failures would not lead to significant losses of life or financial cost. Many cases of embankment failure have been reported involving flooding impact on embankment failure (Ansary & Safiullah, 2002; Tatsuoka, *et. al.*, 2007; Polemio, 2010).

Recent increasing trends of yearly rainfall amount and rainfall intensity during rainy season due to climate change significantly increase geotechnical hazard risk. To quantify the risk of embankment failure, reliability analysis should be

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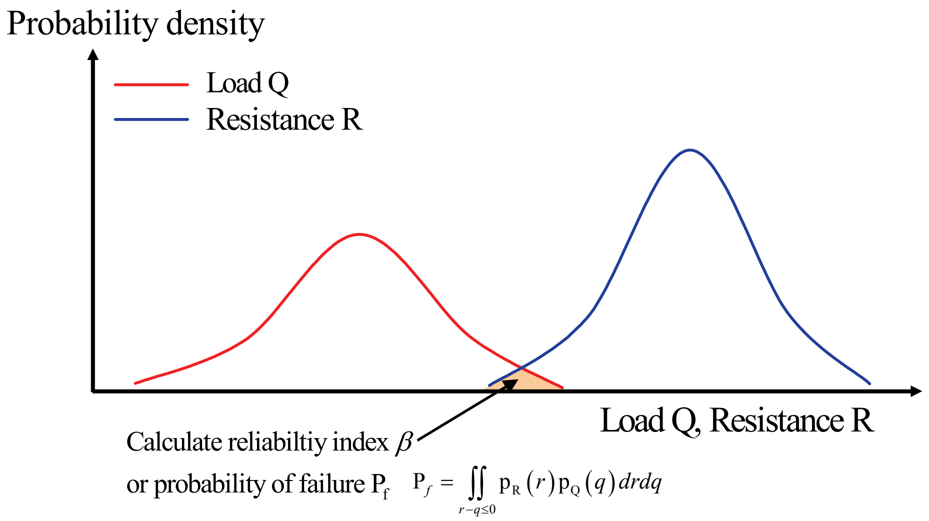


Figure 1. Load and resistance distributions and probability of failure

performed. Reliability analysis in this study merely implies calculation of potential probability of failure.

For the assessment of probability of failure, uncertainties of total load and total resistance should be quantified. As there are many factors influencing loads and resistances and many of these factors have inherently uncertain, load and resistance are expressed as probability density functions, as shown in 〈Figure 1〉. For existing unfailed structures, resistance distributions are located on the right sides of load distributions. For the given load and resistance distributions, probability of failure is related to overlapped area between the load and resistance distributions (〈Figure 1〉). The probability of failure can be analytically calculated by the double integration of joint probability density function with respect to load and resistance.

Embankment stability analysis is more complicated than other typical geotechnical structures, such as piles, shallow foundation, and retaining structures. Embankment stability assessment is similar to that of slopes. Advanced embankment or slope analyses could be done by limit analysis or numerical analysis, such as finite element analysis or finite difference method (Salgado, 2008). However, in this research, to successfully implementation of Gaussian random fields to represent spatial variabilities of soil parameters within homogeneous layers in reliability analysis, simpler analysis method (*i.e.*, limit equilibrium analysis) is used. The complexity in analysis results from generation of numerous potential slip surfaces to find the most critical slip surface.

Typical embankment or slope stability analysis requires to check both short−term and long−term stabilities (Jung, *et. al.*, 2016). Checking both short− and long−term stabilities is critical for nonfrictional soils. However, the soils consisting the embankment in this study are mostly frictional soils; therefore, there expected no significant distinction between short− and long−term stabilities results.

II. EMBANKMENT STABILITY ANALYSIS

1. Conventional Deterministic Analysis

Conventional deterministic analysis of embankment assumes perfect correlation of soil parameters within a homogeneous layer. In other words, scales of fluctuation of soil parameters are infinity. Limit equilibrium analysis determines the most critical slip surface from numerously and randomly generated potential slip surfaces. The minimum factor (the minimum ratio of resisting moment to driving moment) of safety corresponding to the most critical slip surface is named factor (FS) of safety, The FS is determined among the numerously calculated resisting moment–to–driving moment ratios for the generated potential slip surfaces. Early–used methods of slices was Fellenius method (Fellenius, 1936). Many researchers developed their own methods mostly varying assumption on interslice forces between slices and force and moment equilibrium conditions. Later, more advanced limit equilibrium methods have been developed improving the rigorousness of FS calculation (Sarma, 1973).

Calculations of the resisting and driving moments were conducted using the Bishop simplified method (Bishop, 1955). For fast calculation of a FS, the Bishop simplified method assumes no vertical interslice forces between slices. The calculated FS value should exceed the minimum FS value proposed in design codes, and the minimum FS value is determined considering importance of structure. The reasonable FS value for slope and embankment is 1.5, which is considered as a norm in working stress design.

2. Reliability–Based Analysis

Implementing Gaussian random field theory for representation of spatial variabilities of soil parameters was also done in the past research (Fenton, 1990; Uzielli, *et. al.*, 2005; Salgado & Kim, 2014), and its validity was tested to have reasonable results. Different methods of generating Gaussian random field exist and their details can be obtained from the thesis of Fenton (1990). For each soil parameter of each layer, a Gaussian random field is generated independently. All the generated Gaussian random fields reflecting their coefficients (COVs) of variation, expected value, scale of fluctuation are superposed on appropriate locations of the target embankment. Coefficient of variation is defined as a ratio of the standard deviation to the expected value (or mean). Larger coefficient of variation of a variable indicates higher uncertainty of the variable. 〈Figure 2〉 shows Gaussian random fields' superposition for three–layered embankment.

Probability of failure of the "random field" implemented embankment failure is calculated using Monte Carlo simulation technique based on codes programed by Fortran language. The procedure of probability of failure calculation is as follows: (1) Determine reasonable bias factors, COVs, and scales of fluctuation of unit weight (γ), cohesion (c), friction angle (φ) and their correlation coefficient functions; (2) For each layer, generate Gaussian random fields of γ, c, and φ reflecting their bias factors, COVs, expected values, scales of fluctuation; (3) Superpose the generated Gaussian random fields on the embankment geometry; (4) Generate a sufficiently large number of potential slip surfaces and determination of FS and the most

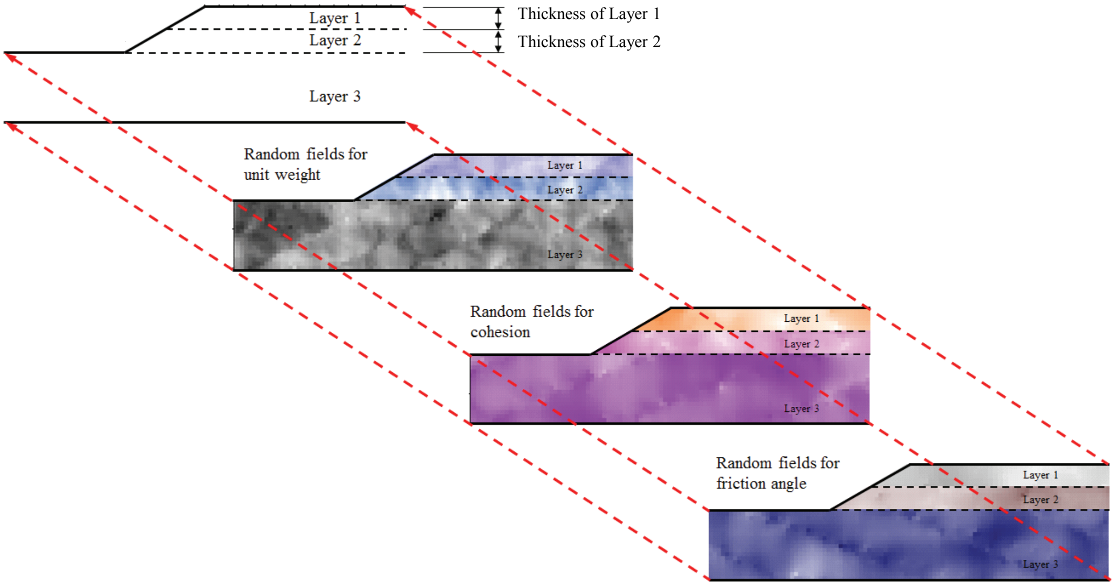


Figure 2. Superposition of generated Gaussian random fields of soil parameters reflecting their uncertainties

critical slip surface (i.e., the driving moment M_d and the resisting moment M_r corresponding to the most critical slip surface); (5) Repeat Steps (1)~(4) N times (N should be adequately large number to produce reliable and stable probability of failure); and (6) Determine probability ($P_f = i/N$) of failure by the counted number (i) of failure cases (cases having $M_d \geq M_r$) out of total repetition (N) of random simulation.

Acceptable target probability of slope or embankment failure varies depending on the importance of the structure (The importance of structure is typically determined considering amount of losses of life and financial cost after its possible failure). However, for normal conditions, Santamarina, *et. al.* (1992) proposed 0.0001 as appropriate lower bound of target probability of failure for slopes and embankments.

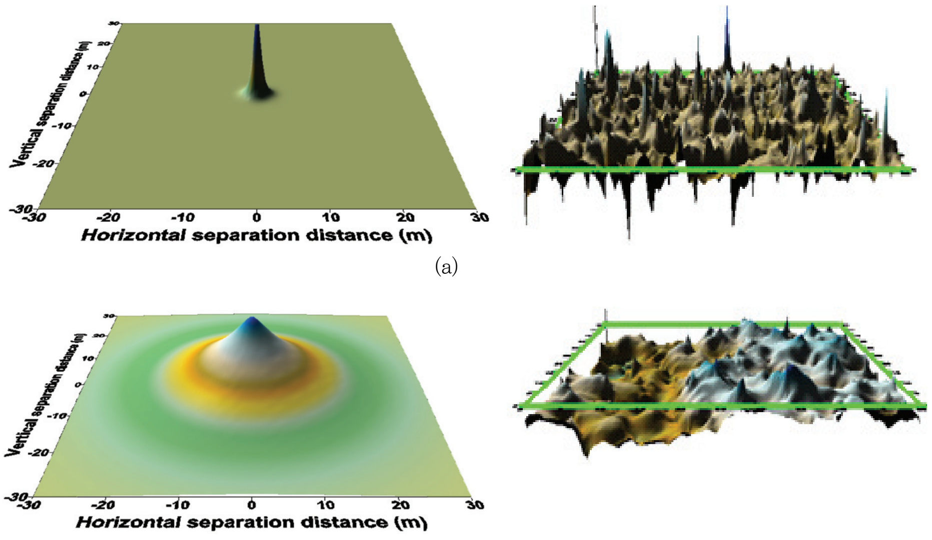
3. Soil Variability Representation

Gaussian random field assumes that a random value at a location of the generated random field has constant expected value and standard deviation. In addition, it is assumed that the correlation between any two points is governed by the correlation coefficient function within a Gaussian random field (〈Figure 3〉). There are many types of correlation coefficient functions; however, Kim (2008) reported that the typically-used correlation coefficient functions do not have significant effect on random field shape. In this study, the following exponential correlation coefficient function is used:

$$\rho(d) = \exp\left(-\frac{2d}{\theta}\right) \tag{1}$$

where d is the distance between two points and θ is the scale of fluctuation.

Consequently, for a given correlation coefficient function, scale of fluctuation is the most important factor governing the shape of random field. 〈Figure 3〉 shows the graphical representation of exponential



(a)

(b)

Figure 3. Graphical representation of correlation coefficient functions and random fields for scales of fluctuation of (a) 1 m and (b) 20 m

correlation coefficient function [Eq. (1)] and generated Gaussian random fields for scales of fluctuation of 1 m and 20 m. For embankment and slope reliability analysis with higher scale of fluctuation, more distinction is found between areas of strong and weak zones; therefore, higher probability of failure is expected.

III. EMBANKMENT DESCRIPTION

The target embankment in this study is located at Nakdong River, Bugok-ri, Dasa-eup, Daegu, Korea. The location and picture view of the target embankment are shown in 〈Figure 4〉. As the embankment is constructed along the river, potential threat of embankment failure exists due to the possibility of unexpected significant water rise in the future.

Based on the extensive site investigation results, the representative cross section of the target representative embankment is determined. The embankment is subdivided into four homogeneous layers: (1) Embankment fill layer, (2) Silty sand layer, (3) Poorly graded sand layer, and (4) Soft rock layer, as shown in Figure 5. The embankment fill is compacted fill soils. The height of the

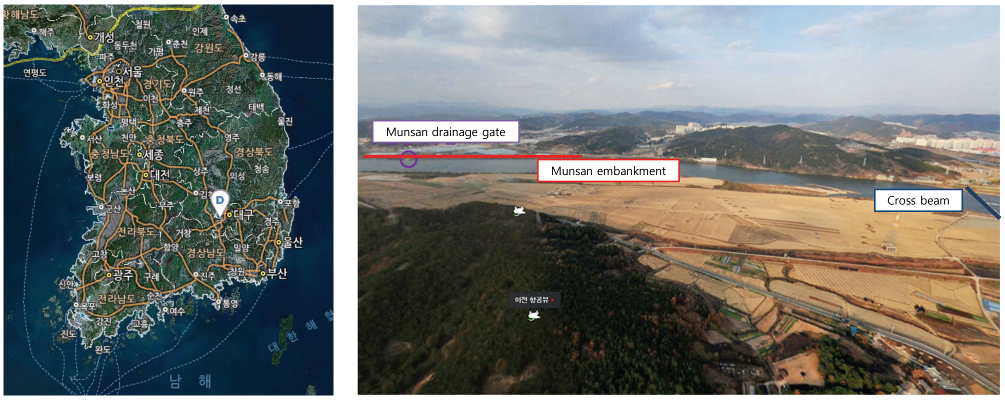


Figure 4. Location and picture view of the target embankment

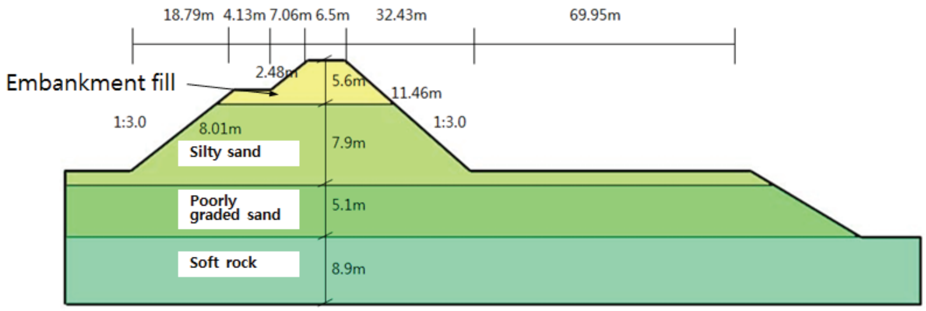


Figure 5. Dimension and soil types of sublayers of embankment.

Table 1. Material properties used in the analysis

	Unit Weight γ (kN/㎥)	Friction Angle φ (°)	Cohesion c (kPa)	Elastic Modulus E (MPa)	Permeability k (cm/s)
Embankment Fill	18	28	10	15	8.0×10−4
Sedimented Silty Sand (SM)	17	25	5	6	2.0×10−3
Sedimented Poorly Graded Sand (SP)	19	30	–	20	8.0×10−3
Soft Rock	24	33	300	2,000	5.0×10−6

embankment is about 12∼13 m from the toe. The river is located at the left side of the embankment in 〈Figure 5〉.

From the site investigation results of 15 boreholes near the embankment, the determined soil properties of each layer are summarized in 〈Table 1〉.

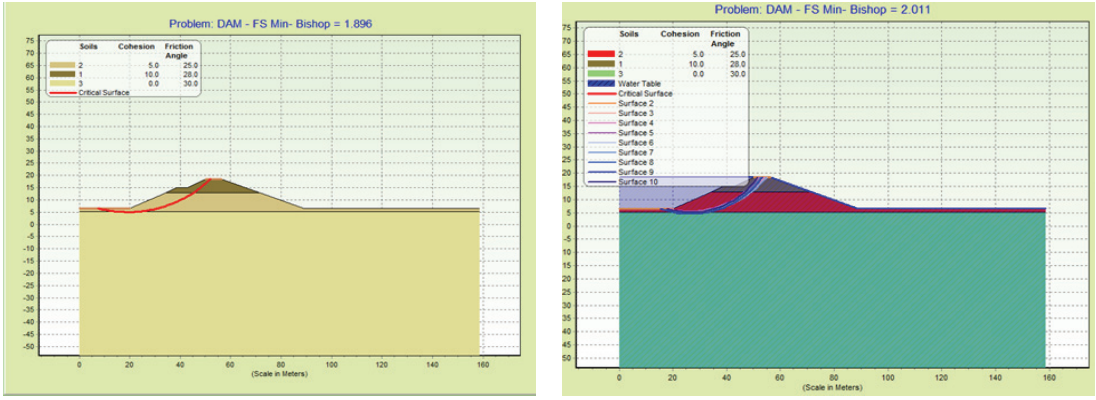
Ⅳ. ANALYSIS RESULTS

1. Conventional Deterministic Analysis

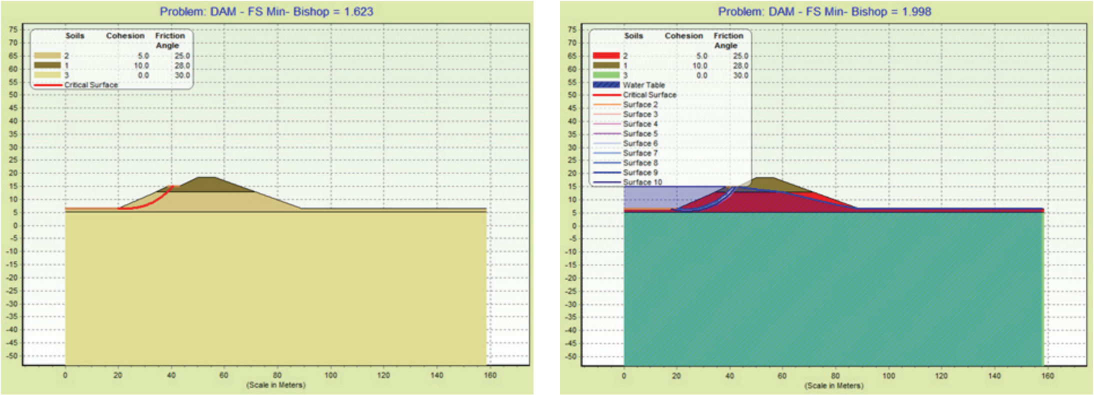
As the target embankment has two crests, three stages of deterministic stability analysis were conducted. As shown in 〈Figure 6〉, the minimum governing FS value was 1.623 without considering water table. This calculated FS value exceeds the proposed FS (1.5) in the design codes (Caltrans, 2014; TMR, 2015; AASHTO, 2010). However, under different water table level assumptions, the FS value increased when potential slip surfaces are located (or faced) against the water tables while it deceased when high water table is located behind potential slip surfaces. The lowest FS value under various water table levels was as low as 1.157. Therefore, careful examination of probability of embankment failure reliability is necessary.

2. Reliability-Based Analysis

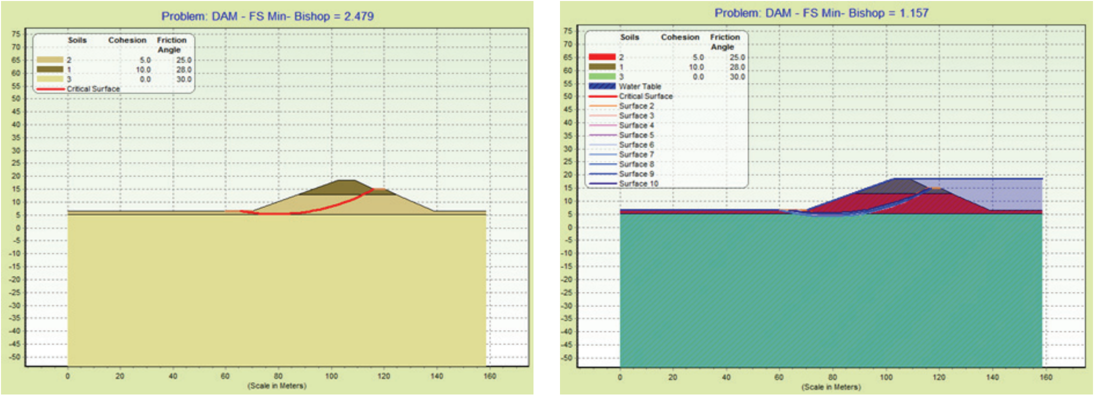
In generation of Gaussian random fields of each layer's soil properties (γ, c, and φ), the expected values of the soil properties are assumed to be equal to their nominal values. Therefore, the bias factors of all the soil parameters are unity. In reality, these bias factors may not be 1; however, quantification of soil parameters' bias factors is impossible due to imperfection in soil sampling and in assessing true values from in-situ testing. Coefficients (COVs) of variation of γ, c, and φ are assumed to be 0.1, 0.4, and 0.1 (COVγ = 0.1, COVc = 0.4, and COVφ = 0.1). These COV values are conservatively assessed values based on extensive literature review from the thesis of Kim (2008). Similarity to the COV values, conservative scales (θ) of fluctuation were assumed. The assumed scales of



(a) FS = 1.896 〉 1.5 (b) FS = 2.011



(c) FS = 1.623 〉 1.5 (d) FS = 1.998



(e) FS = 2.479 〉 1.5 (f) FS = 1.157

Figure 6. Deterministic analysis of embankment (a) Case 1 without water table (FS=1.896); (b) Case 1 with assumed water table (FS=2.011); (c) Case 2 without water table (FS=1.623); (d) Case 2 with assumed water table (FS=1.998); (e) Case 3 without water table (FS=2.479); (f) Case 3 with assumed water table (FS=1.157).

fluctuation of γ, c, and φ were 20 m following the assumptions in previous research (Salgado & Kim, 2014; Kim, 2008). Determination of realistic scale of fluctuation of a soil parameter requires serious effort by narrow measurements of soil parameters in vertical and horizontal directions.

From Monte Carlo simulation of the target embankment of this paper without considering water table, sufficient number of repetitive simulations (or calculations of FS) of random embankment was performed to produce reliable probability of failure. The total simulated number (N) to calculate single probability of failure was 485,092 (N = 485,092). Only 7 failures were

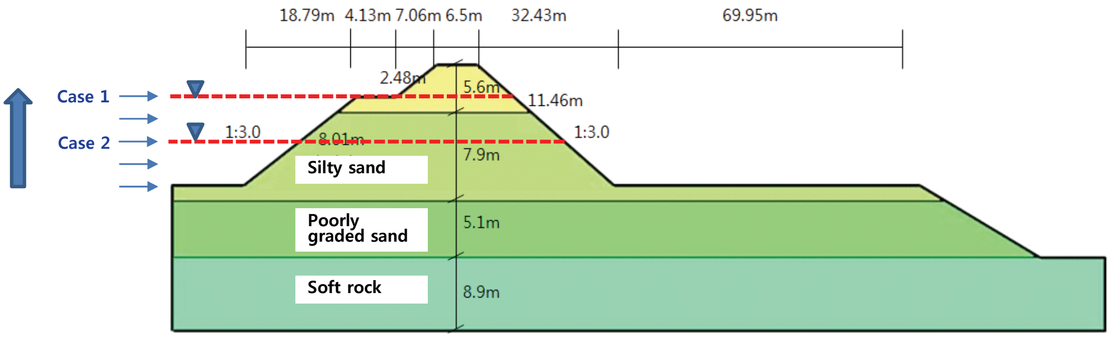


Figure 7. Performed two different water table levels

observed from N simulations. Therefore, the probability of embankment failure is 7/485,092 (=1.443×10^{-5}). This probability of embankment failure is less than the suggested lower bound (0.0001) of the target probability of failure (Santamarina, *et. al.*, 1992). It can be concluded that sufficient safety margin exists on embankment without water table level increase.

3. Effect of Water Table Rise on Probability of Failure

Recently, climate change is one of the key issues in Civil engineering. For the embankments exposed to river or water, disaster mitigation plan should be made based on the priority determined from risk analysis. Against unexpected possible water rise, additional reliability analyses were performed for two different water table level increase scenarios (Cases 1 & 2 in ⟨Figure 7⟩). For Case 1, water table level is assumed to be the same level of the lower crest. The calculated probability of failure was estimated as high as approximately 10%. When the water table level of Case 1 is lowered to half from the left toe of the embankment, the probability of embankment failure decreased to approximately 0.1%.

V. CONCLUSIONS

Degrees of spatial variabilities of soil parameters within homogeneous soil layers for lager dimension embankment should be quantified and reflected in assessment of its probability of failure. It is because of the significant effects of the soil parameters' spatial variabilities on embankment safety. Gaussian random field theory is implemented to represent soil parameters' spatial variabilities. Conventional deterministic embankment stability analysis produced higher factors of safety under no water table conditions; however, very low factor (1.157) of safety was found under worst water table level assumption. From the reliability analysis results, probability (1.443×10^{-5}) of embankment failure was sufficiently low to conclude it safe. Reliability analyses varying water table conditions reveal a significant effect of water table rise on probability of embankment failure. It may require disaster mitigation plan for unexpected significant rise of water table possibly resulted from climate change.

However, the scale of fluctuation values used in this study may differ from the real site due to complexity and difficulty of site investigation for the assessment of scale of fluctuation. To perform more accurate assessment of potential probability of embankment failure, realistic ground water flows for different water table conditions should reflected in the analyses.

감사의 글

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (No. 2016915228).

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Received: Sep. 2, 2016 / Revised: Sep. 23, 2016 / Accepted: Sep. 26, 2016

지반정수의 공간적인 변동성을 고려한 제방의 신뢰성 분석

국문초록 제방의 안정성을 평가하기 위하여 결정론적인 해석과 신뢰성 해석을 수행하였다. 해석 대상인 제방은 경상북도 고령지역에 존재하는 제방으로 해석을 위해 필요한 제방 형상과 지반 물성치는 상세 지반조사 결과에 근거하여 결정하였다. 제방의 활동 모멘트와 저항 모멘트는 Bishop simplified method를 이용하여 평가하였다. 제방의 신뢰성 분석을 위하여, 균질하다고 가정할 수 있는 영역 내에서의 지반 정수의 공간적인 변동성을 재현하기 위하여 Gaussian random field 이론을 적용하였다. 제방 주변에 수위가 낮을 경우에는 결정론적인 방법으로 계산한 제방 안전율은 설계기준에 제시된 최소 안전율보다 크게 평가되었고, 신뢰성 분석을 통하여 평가된 잠재된 제방 파괴확률은 목표 기준보다 낮아 안전한 것으로 평가되었다. 하지만 수위가 올라가면 제방 안전율은 떨어지고 제방의 파괴확률도 급격히 증가하는 것을 확인하였다.

주제어 : 제방, 파괴 확률, 수위, 신뢰성 분석

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