Proc. of the 8th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Jinsong Huang, D.V. Griffiths, Shui-Hua Jiang, Anna Giacomini and Richard Kelly
©2022 ISGSR Organizers. *Published by* Research Publishing, Singapore.
doi: 10.3850/978-981-18-5182-7_13-004-cd

ISGSR 2022

Railway Embankment Quality Control Based on Feature Extraction by Singular Value Decomposition and Bayesian Inference

Kohei Kasahara[1], Susumu Nakajima[2], Hidetoshi Nishioka[3] and Yu Otake[4]

[1]Structures Technology Division, Railway Technical Research Institute,
2-8-38 Hikari-cho, Kokubunji-shi, Tokyo, Japan.
E-mail: kasahara.kohei.70@rtri.or.jp
[2]Structures Technology Division, Railway Technical Research Institute,
2-8-38 Hikari-cho, Kokubunji-shi, Tokyo, Japan.
E-mail: nakajima.susumu.99@rtri.or.jp
[3]Faculty of Science and Engineering, Chuo University,
1-13-27 Kasuga, Bunkyo-ku, Tokyo, Japan.
E-mail: nishioka@civil.chuo-u.ac.jp
[4]Department of Civil and Environmental Engineering, Tohoku University,
6-6-06 Aza-Aoba, Aramaki, Aoba-ku, Sendai, Japan.
E-mail: yu.otake.b6@tohoku.ac.jp

Abstract: We developed an estimation method for the stress-strain curve of soil using the observational information of embankment that can be obtained on site. In the proposed method, the stress-strain curve is estimated using Bayesian linear regression with observed information after summarizing the data from triaxial compression test results and grain size analysis results for various soil materials by singular value decomposition. This method makes it possible to predict the ground strength characteristics such as the maximum internal friction angle and the residual internal friction angle from the deformation characteristic information of the elastic region, such as the coefficient of subgrade reaction. Moreover, this method allows the prediction of the deformation performance of the soil over a wide range of strain levels. It has the potential to provide immediate confirmation of the performance of railway embankments during construction. In addition, this method can be used to evaluate the seismic resistance of existing embankments and design seismic reinforcement.

Keywords: Bayesian Inference; Singular value decomposition; Ground strength characteristics; Embankment.

1 Introduction

In Japan, when a railway embankment is designed, the stability of the embankment is verified by using the strength parameters (c, ϕ) of the soil. On the other hand, railway embankments are constructed based on soil materialregulations and construction management regulations (degree of compaction and coefficient of subgrade reactionK_{30}-value). Under the current Earth structure standards in Japan(Ministry of Land, Infrastructure, Transport and Tourism 2007), it is not directly confirmed whether the strength parameters (c, ϕ) of the design are performed after construction.Instead, such soil material regulations and construction management regulations are determined based onexperience and verification test results. Therefore, major problems have not occurred when an embankment is constructed using conventional soil materials.

On the other hand, recently, the demand for construction generated soil and tunnel spoil, which has not been used in the past, has increased in Japanese railway embankments in order to reduce the costs and the environmental load associated. Furthermore, since the overseas expansion of Japanese railway technology has been promoted in Japan, it is expected that the demand for constructing Japanese-standard railway embankments using non-Japanese soil materials will increase in the future.However, since construction-generated soil materials and non-Japanese soil materials are outside the range of experience and verification tests, there is a problem that the current Japanese construction management regulations cannot be directly applied to these materials. Therefore, even for such materials that have not been used in the past, it is required to develop a quality control method to ensure the same quality of embankment as in the past.

Under these circumstances, we are attempting to organize construction management methods according to the strength of the embankment as a method of controlling embankment quality regardless of the qualitative material classifications that were previously defined.In this paper, as a first step, we developed an estimation method for the stress-strain curve of soil using the observational information of embankment that can be obtained on site.

2 Quality Control method Based on Feature Extraction

Ching et al. (Jianye Ching and Kok-Kwang Phoon, 2019)proposed a method (MUSIC) to estimate the ground characteristics using multivariate probabilitydistribution models from the generic database with various soil quality data, and from the site-specific data with alimited amount of data.

In this research, by applying this idea, we developed a method to estimate the stress-strain curve of soil (this information cannot be observedon site) from observed informationon site. Furthermore, in the proposed method, the quality control of the embankment can be performed by calculating the strength of the embankment from the estimated curve.The proposed method manages the quality of the embankment in the following steps.

Step 0. Preparation

First, we prepare a learning database that stores the physical test data and the construction data for various soil materials. The database stores the main modal functions (orthogonal base functions) when the stress-strain data matrix $\boldsymbol{X} \in \mathbf{R}^{n \times m}$ of the triaxial compression test is dimensionally compressed by singular value decomposition(Eq. (1)). Here, *n* means the number of strain steps of the stress-strain data, and *m* means the number of samples of training data.In this study, we constructed a database on the basis of the results of the triaxial compression test conducted by Fujimoto et al (Tatsuki Fujimoto, Kohei Kasahara, Susumu Nakajima, Yoshitaka Tomida, 2020).

$$\boldsymbol{X} = \boldsymbol{U}\boldsymbol{D}\boldsymbol{V}^{\boldsymbol{T}} \approx \boldsymbol{U}_r\boldsymbol{D}_r\boldsymbol{V}_r^{\boldsymbol{T}} = \boldsymbol{U}_r\boldsymbol{\alpha}_r \tag{1}$$

where, $\boldsymbol{U}$ is a matrix in which left singular vectors are arranged (basal function matrix), $\boldsymbol{D}$ is a diagonal matrix having singular values as diagonal components, and $\boldsymbol{V}$ is a matrix in which right singular vectors are arranged.$\boldsymbol{D}_r\boldsymbol{V}_r^{\boldsymbol{T}}$ is described as the constituent coefficient $\boldsymbol{\alpha}_r$.The subscript “*r*” means information compression up to the *r* dimension.

Step 1. Estimation of stress-strain curve

Using the observed information obtained during embankment construction, the stress-strain curve is estimated by Bayesian linear regression from Eq. (2) to (4).

$$\boldsymbol{\alpha} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_m \end{bmatrix} = \begin{bmatrix} \alpha^{est} \\ \alpha^{obs} \end{bmatrix}, \boldsymbol{\mu} = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_m \end{bmatrix} = \begin{bmatrix} \mu^{est} \\ \mu^{obs} \end{bmatrix}, \boldsymbol{\Sigma} = \begin{bmatrix} \sigma_1^2 & \sigma_{12} & \cdots & \sigma_{1m} \\ \sigma_{21} & \sigma_2^2 & & \sigma_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{m1} & \sigma_{m2} & \cdots & \sigma_m^2 \end{bmatrix} = \begin{bmatrix} \boldsymbol{\Sigma}_{11} & \boldsymbol{\Sigma}_{12} \\ \boldsymbol{\Sigma}_{21} & \boldsymbol{\Sigma}_{22} \end{bmatrix} \tag{2}$$

$$\boldsymbol{\mu}_{\alpha^{est}|\alpha^{obs}} = \boldsymbol{\mu}^{est} + \boldsymbol{\Sigma}_{12}\boldsymbol{\Sigma}_{22}^{-1}\left(\boldsymbol{\alpha}^{obs} - \boldsymbol{\mu}^{obs}\right) \tag{3}$$

$$\boldsymbol{\sigma}^2_{\alpha^{est}|\alpha^{obs}} = \boldsymbol{\Sigma}_{11} - \boldsymbol{\Sigma}_{12}\boldsymbol{\Sigma}_{22}^{-1}\boldsymbol{\Sigma}_{21} \tag{4}$$

Where, $\boldsymbol{\alpha}$ is the constituent coefficient, $\boldsymbol{\mu}$ is the average vector of $\boldsymbol{\alpha}$, and $\boldsymbol{\sigma}^2$ is the variance vector of $\boldsymbol{\alpha}$. $\boldsymbol{\Sigma}$means the covariance matrix of each observation parameter.The superscript “est” means the estimation vector, and the superscript “obs” means the observation vector.Using the $\boldsymbol{\alpha}$ obtained from these equations, the stress-strain curve of the soil is estimated by reconstructing $\boldsymbol{X}^{est}$ in equation (5).

$$\boldsymbol{X}^{est} = \boldsymbol{U}_r\boldsymbol{\alpha}_r^{est} \tag{5}$$

Step 2. Verification of embankment quality

For the estimated soil stress-strain curve, the maximum internal friction angleϕ_{peak} and residual internal friction angleϕ_{res}arecalculated from the Mohr's circle of stress based on the *c*-0 method with reference to the current Earth structure standards in Japan (Eq. 6to Eq.7).

$$\emptyset_{peak} = \boldsymbol{sin}^{-1}\left(\frac{\sigma_1^{peak} - \sigma_3}{\sigma_1^{peak} + \sigma_3}\right) \tag{6}$$

$$\emptyset_{res} = \boldsymbol{sin}^{-1}\left(\frac{\sigma_1^{res} - \sigma_3}{\sigma_1^{res} + \sigma_3}\right) \tag{7}$$

Where, $\sigma_1$means the axial force and $\sigma_3$means the confining pressure.This method makes it possible to confirm whether the strength parameters of the design are performed after construction. As a result of quality confirmation,If the design strength is not satisfied perform, Step 1 (estimation of stress-strain curve) and Step 2 (verification of embankment quality) after rolling the embankment again.If it is confirmed that the strength of the embankment after construction satisfies the design strength by repeating these steps, the construction is completed.

These steps are the proposed method of the quality control method for embankments.By using this proposed method, the quality of the embankment can be controlled regardless of the material. Moreover, the ground strength characteristics such as the maximum internal friction angle and the residual internal friction angle can be predicted from the deformation characteristic information of the elastic region such as the coefficient of subgrade reaction. This method allows the prediction of the deformation performance of the soil over a wide range of strain levels. It has the potential to provide immediate confirmation of the performance of railway embankments during construction.

In this method, what kind of observed information is acquired during construction is important.Therefore, in Chapter 3, we confirm the relationship between the observed parameters and the estimation accuracy of the stress-strain curve.

3 Examination of parameters used for quality control

In order to confirm the relationship between the observation parameters and the estimation accuracy of the stress-strain curve, the examination inside the training data range is performed in Chapter 3.1, and the examination outside the training data range is performed in Chapter 3.2.

When utilizing the proposed method in actual embankment construction, it is assumed that the stress-strain curve is estimated using the observation parameters obtained on site. However, in this paper, as a basic study, the stress-strain curve is estimated using the observation parameters obtained in the triaxial compression test.

3.1Interpolation

As an interpolated study within the training data range, the analysis is performed under the conditions shown in Table 1. First, in Case A1, the observation parameters are the degree of compaction D_c and the coefficient of subgrade reaction K_{30}, which areused in the current construction management of railway embankments in Japan. In this study, K_{30} is calculated by deformation modulus E obtained in the triaxial compression test with reference to the current Earth structure standards in Japan (Eq. (8)).

$$K_{30} = 2.2K_{75} = 2.2 \cdot \frac{2E}{\pi d(1-\nu^2)} \tag{8}$$

Where, E is deformation modulus (ε = 0.5%) [MN/m^2], d is radius of loading plate (0.75/2) [m], $\nu$is Poisson's ratio (assumedν= 0.4). In actual construction, K_{30} is measured by loading with portable FWD (Falling Weight Deflectometer) test or method for plate load test on soil for road (JIS A 1215)shown in Figure 1.

Secondly, in Case A2, since S_r has been found to have a large effect on the strength of the embankment in recent studies (Fumio Tatsuoka, Antonio G. Correia 2016, Fumio Tatsuoka, Kenji Fujishiro, Kazuyoshi Tateyama, Shohei Kawabe, Yoshiaki Kikuchi 2016), the degree of saturation S_r is added to the observation parameters. Furthermore, in Case A3, U_c, U_c' and F_c are added to the observation parameters as parameter of grain size distribution (*PGS*). Conventionally, information about grain size distribution such as *PGS*is used only to determinewhether or not the material regulation is satisfied.Therefore, although its information is not used for theconventional embankment construction management, its informationis set as the parameters in this study because it is important information showing the characteristics of the soil.

Table 1. Analysis conditions(interpolation)

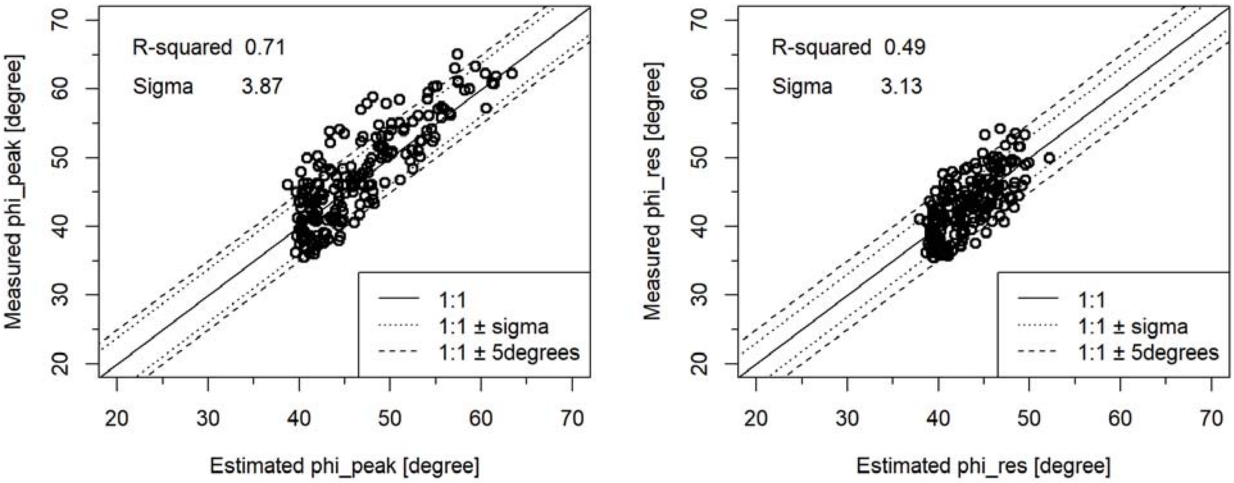
Case	Parameter*	Remarks
Case A1	D_c, K_{30}	No information about grain sizedistribution
Case A2	D_c, K_{30}, S_r	
Case A3	D_c, K_{30}, S_r, *PGS*	With information about grain sizedistribution

**PGS*: Parameter of grain sizedistribution (U_c, U_c', F_c)

Figure 2to 4 show the analysis results. The left figure shows the relationship between the measured values and estimated values of the maximum internal friction angle ϕ_{peak}, and the right figure shows the relationship between the measured values and estimated values of the residual internal friction angle ϕ_{res}. Figure 2 shows that the R-squared of ϕ_{peak} is 0.71 and of ϕ_{res} is 0.49. Therefore, when only the D_c and K_{30} are used as parameters, the result of the estimation is low accuracy. Figure 3 shows that although the R-squared is slightly improved (ϕ_{peak} is 0.75 and ϕ_{res} is 0.53) by adding S_r to the observation parameter, the estimation accuracy is not improved significantly.

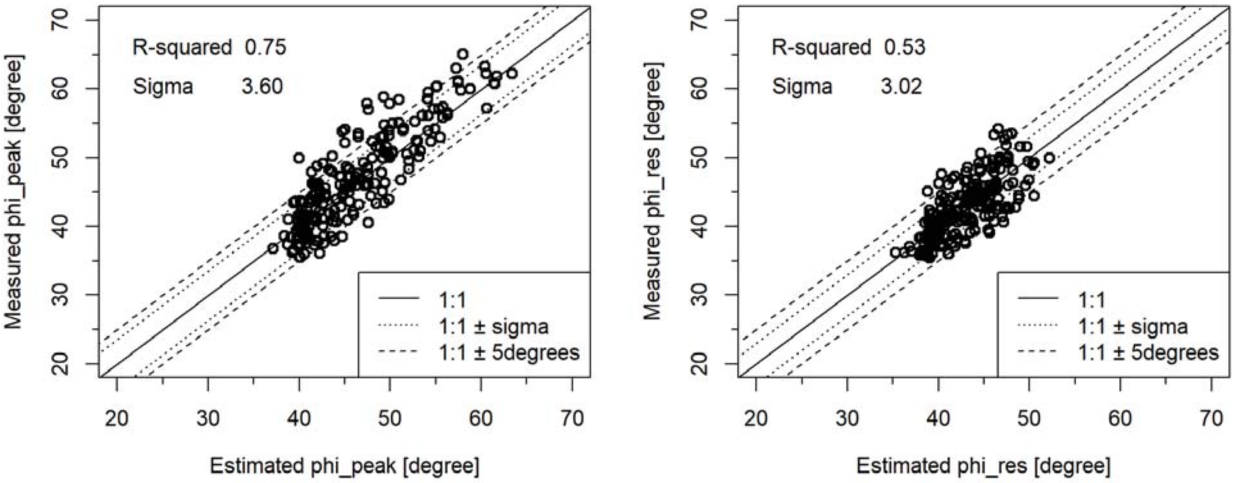
(a) Portable FWD test (b) Method for plate load test on soil for road

Figure 1. Loading method to measure K_{30} on site



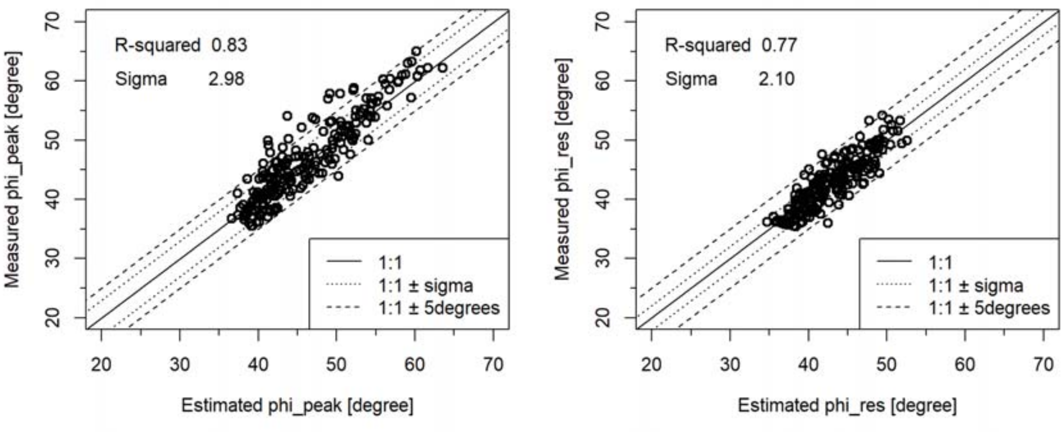
(a) ϕ_{peak} (b) ϕ_{res}

Figure 2. Result of estimation (interpolation)【Case A1: D_c, K_{30}】



(a) ϕ_{peak} (b) ϕ_{res}

Figure 3. Result of estimation (interpolation)【Case A2: D_c, K_{30}, S_r】



(a) ϕ_{peak} (b) ϕ_{res}

Figure 4. Result of estimation(interpolation) 【Case A3: D_c, K_{30}, S_r, *PGS* (U_c, U_c’, F_c)】

On the other hand, from Figure 4, it is found that the estimation accuracy is greatly improved by adding the parameters related to the particle size information. Therefore, it is considered that the particle size parameters (U_c, U_c', F_c) can accurately express the typical characteristics of soil regarding the particle size information. From the above results, it is found that the estimation accuracy of the internal friction angle is greatly improved by considering the particle size information (*PGS*) as observed information in addition to the compaction degree D_c, the ground reaction force coefficient K_{30} value, and the saturation degree S_r.

3.2 Extrapolation

As an extrapolated study in the verification data, the analysis is performed under the conditions shown in Table 2. First, in Case B1, D_c, K_{30}, and S_r are used as observation parameters. Furthermore, in Case B2, particle size information (*PGS*) is added. The conditions for the verification data are shown in Table 3.

Figures 5 to 6 show the estimation results of the stress-strain curve and the residuals at each strain level. Here, the figure on the left is the result of Sample 1, the figure in the middle is the result of Sample 2, and the figure on the right is the result of sample 3. From Figure 5, when D_c, K_{30}, and S_r are used as observation parameters, the measured value and the estimated value are generally the same for sample 1 with a low degree of compaction. However, in samples 2 and 3 with a high degree of compaction, the difference between the measured value and the estimated value is large. Figure6 show that the estimation accuracy of samples 2 and 3 can be improved by considering the particle size information. Furthermore, it is found that although the estimation accuracy of the maximum point of sample 3 is not high, the variation of each sample in residual strain can be reduced by considering the particle size information.

From the above results, it is found that the estimation accuracy is improved by considering the particle size information as observation information even in the case of extrapolation. Therefore, when estimating the stress-strain curve using the proposed method, it is important to observe the particle size information of soil used on site.

Table 2. Analysis conditions(extrapolation)

Case	Parameter*	Remarks
Case B1	D_c, K_{30}, S_r	No information about grain sizedistribution
Case B2	D_c, K_{30}, S_r, *PGS*	With information about grain sizedistribution

**PGS*: Parameter of grain sizedistribution (U_c, U_c’, F_c)

Table. 3 Conditions of verification data(extrapolation)

Sample	Conditions		
Sample1	Gravelly soil (GFS)	S_r= 81%	D_c= 90%
Sample2			D_c= 95%
Sample 3			D_c= 98%

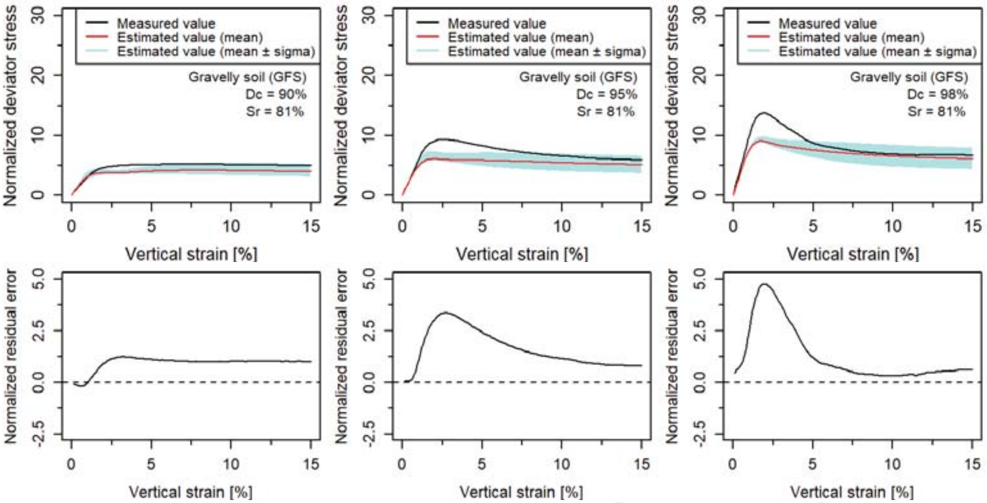


Figure 5. Result of estimation(extrapolation) 【Case B1:D_c, K_{30}, S_r】

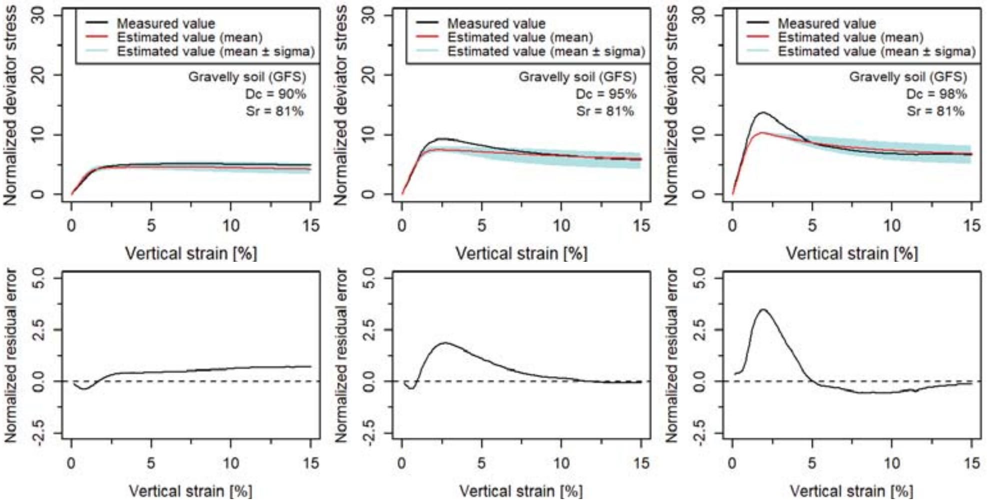


Figure 6. Result of estimation(extrapolation) 【Case B2: D_c, K_{30}, S_r, *PGS* (U_c, U_c', F_c)】

4 Conclusion

We developed an estimation method for the stress-strain curve of soil using the observational information of embankment that can be obtained on site. This method makes it possible to predict the ground strength characteristics such as the maximum internal friction angle and the residual internal friction angle from the deformation characteristic information of the elastic region,such as the coefficient of subgrade reaction. Moreover, this method allows the prediction of the deformation performance of the soil over a wide range of strain levels. Therefore, it has the potential to provide immediate confirmation of the performance of railway embankments during construction. In addition,since this method can estimate the stress-strain curve at each point of the embankment on site, it is considered possible to apply this method to the seismic performance verification of existing embankments and seismic retrofitting design.

References

Supervised by Ministry of Land, Infrastructure, Transport and Tourism, Edited by Railway Technical Research Institute, Design Standards for Railway Structures and Commentary (Earth structure), *Maruzen Publishing Co. Ltd 2007 (in Japanese)*.

Fumio Tatsuoka, Antonio G. Correia, Importance of Controlling the Degree of Saturation in Soil Compaction, *The 3rd International Conference on Transportation Geotechnics (ICTG 2016)*, Vol. 143, pp. 556-565, 2016.

Fumio Tatsuoka, Kenji Fujishiro, Kazuyoshi Tateyama, Shohei Kawabe, Yoshiaki Kikuchi, Properties of compacted soil as a function of dry density and the degree of saturation, *The 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering*, Vol. 2, No. 4, pp. 247-252, 2016.

Jianye Ching, Kok-Kwang Phoon, Constructing Site-Specific Multivariate ProbabilityDistribution Model Using Bayesian Machine Learning, *Journal of Engineering Mechanics*, Volume 145, Issue 1, 2019.

Tatsuki Fujimoto, Kohei Kasahara, Susumu Nakajima, Yoshitaka Tomida, Examination of degree of compaction, rigidity and strength of railway embankment by triaxial compression test, *55th Geotechnical Society Presentation, 2020 (in Japanese)*.