Influence of water-level rise on instability of dykes

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ABSTRACT

This study aims to find a suitable answer to the question of "Which mechanical properties of dyke soils can contribute to a greater increase stability of dykes undergoing rapid rise in water level caused by torrential rainfall?" Numerical experiments for the modeled ground and dyke were conducted based on total stress analysis with consideration of the influences of unit weight, rigidity, internal friction, and cohesion on dyke stability. Results of a parametric evaluation show that increased cohesion is the most important contributing factor for increased stability of dykes undergoing water-level rise (WLR). In other words, results imply, from a practical perspective, that such adaptive measures as acceleration of consolidating dyke soils by compaction at the bottom and addition of cement during dyke construction at the top of dykes increase the stability of dykes undergoing WLR caused by extreme precipitation in the context of climate change.

KEYWORDS: Stability, Improvement, Dyke, Cohesion, Extreme event, Water-level rise (WLR)

1. INTRODUCTION

Climate impacts have recently increased riverine dyke instability. That riverine has been damaged by flood in front dykes and scour behind them, particularly during severe climate change-induced extreme rainfall. The damage in dykes in the Kinu River occurred in torrential rainfall in 10 September 2015 in Ibaraki, Japan, is a typical example. To reduce those negative influences, fundamental knowledge of geotechnical engineering requires the (i) utilization of well-graded soils, (ii) sufficient compaction and (iii) chemical improvement and mechanical reinforcement in cases of insufficient stability.

To address the requirements stated above, numerical experiments for a modeled ground and dyke were conducted based on total stress analysis with consideration of the influences of unit weight, rigidity, internal friction, and cohesion of dykes on dyke stability. Although effective stress analysis is also necessary particularly for taking the effects of seepage forces in dykes into consideration, this issue is out of the purpose in the current paper and will be described in the separate paper.

2. MODEL DYKE FOR ANALYSIS

The typical configuration of riverine dykes is presented in Fig. 1. Roughly speaking, dykes are characterized by the following.

i) Gentle slope of the frontal surface
ii) Constituent sandy or silty materials

The model dyke in Fig. 1 is assumed to be founded on two layers of sandy clay and fine sand.

The dyke is assumed to consist of sand for simplicity because the paper presents an exploration of what kind of material improvement of dyke soils is expected to contribute to maintaining and increasing the stability of dykes against severe events triggered by climate change.

3. PARAMETERS USED FOR NUMERICAL ANALYSES

To improve and reinforce riverine dykes, and particularly those undergoing severe weather caused by climate change, there are two methods of structural reinforcement of dyke systems and material improvement of dyke soils (Recio and Yasuhara, 2005; Yasuhara and Recio, 2007; Yasuhara et al., 2012). This study specifically examines the latter case, i.e., what mechanical properties should be improved for increasing dyke stability against severe weather such as strikes by sudden rise in water level by extreme rainfall (Sato et al., 2013).

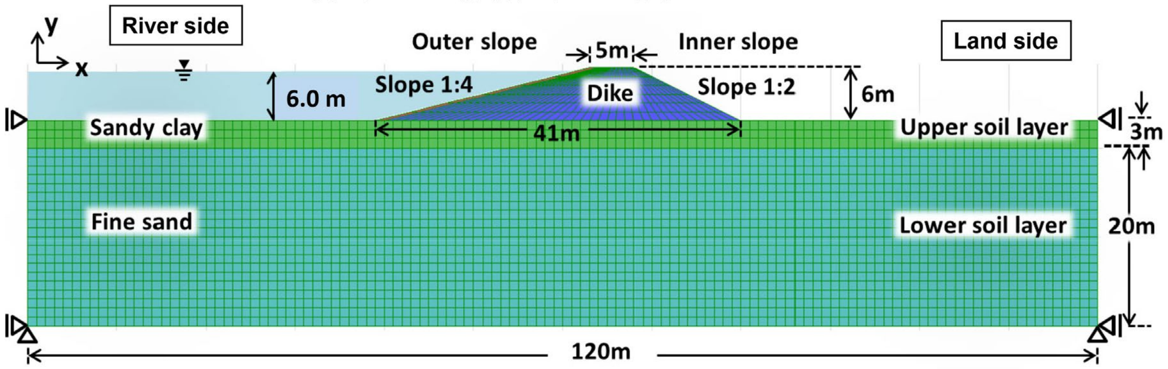


Figure 1 Configuration of riverine dykes for numerical analysis

Table 1 Parameters of dykes used for numerical analysis

	Case 1: density			Case 2:internal frictional angle			Case 3 : cohesion			Case 4: stiffness		
	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3
K (MPa)	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
c (kPa)	0	0	0	0	0	0	0	10	20	0	0	0
r_{sat} (t/m^3)	1.85	1.95	2.05	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
ϕ (deg)	22.5	22.5	22.5	22.5	25	30	22.5	22.5	22.5	22.5	22.5	22.5
G (MPa)	5.76	5.76	5.76	5.76	5.76	5.76	5.76	5.76	5.76	5.76	11.5	17.3
E(Mpa)	14.98	14.98	14.98	14.98	14.98	14.98	14.98	14.98	14.98	14.98	26.40	35.52
ν	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.15	0.03

Numerical analysis was also conducted to explore the engineering measures to be taken in accordance to each situation for increasing dyke stability, particularly undergoing severe precipitation conditions in the context of climate change.

The unit volume weight, γ_t, as an index property, bulk modulus, K, internal friction angle, ϕ, cohesion, c, and stiffness, G, are selected as indexes and mechanical parameters of the dyke soil which fundamentally influence the behavior of dyke and foundation systems at the riverine. Those are presented in Table 1.

For numerical analysis, we also assume parameters for subsoils of clayey and sandy layers which constitute foundations. Those parameters are presented in Table 2.

Table 2 Parameters of foundation soils

Index	Layer ①	Layer ②
Bulk modulus K (MPa)	8.77	20.8
Cohesion c (kPa)	10	0
Unit volume weight r_{sat} (kg/m^3)	2038.7	2140.7
Internal friction angle φ (deg)	11.5	30
Stiffness G (MPa)	3.81	9.61

4. NUMERICAL ANAYSIS

4.1 Analytical Method

Two-dimensional finite element method was adopted to demonstrate which mechanical parameters give influences on deformation and instability behavior of dykes founded on two-layered subsoils undergoing water-level rise (WLR).

4.2 Constitutive Model Used for FEM

Numerical analysis using FEM with the constitutive equation incorporating the hardening function of the complete elasto-plasticity and the Mohr–Coulomb yield function given as

$$f = \sigma_m \sin\phi + \bar{\sigma}\cos\theta - \frac{\bar{\sigma}}{\sqrt{3}\sin\theta \, \sin\phi} - c = 0 \tag{1}$$

where ϕ stands for internal frictional angle, σ_m signifies mean principal stress, θ denotes Lode's angle, and σ' represents the corresponding stress defined as

$$\bar{\sigma} = \sqrt{J_2} = \sqrt{1/2 s_{ij} s_{ij}} \tag{2}$$

where J_2 is the invariant of deviator stress tensor, and s_{ij} represents the deviator stress tensor.

4.3 Analytical Condition and Method

4.3.1 Analytical condition

The following boundary conditions are assumed for analysis.

i) Horizontal direction of the lateral side of ground is fixed

ii) Horizontal and vertical directions at the bottom of ground are fixed

4.3.2 Analytical method

We started to conduct self-weight analysis in which the step loads from coastal dykes were applied to the ground. Results from the first 10 steps of self-weight were assumed as the initial condition. Thereafter, further step loads were applied up to the 490 steps.

5. RESULTS OF NUMERICAL ANALYSIS

5.1 Overall Trend of Dyke Displacement and Failure

Results from parametric numerical analyses presented show the following:

i) For cases with variation of the unit volume weight and assumed zero cohesion, displacement at the top of dykes is large, leading to failure.

ii) For cases of cohesion greater than 10 kPa and internal frictional angle larger than 25.0°, no dyke failure occurs because of the low self-weight of dykes.

5.2 Strength Parameter Effect on Dyke Stability

Table 3 presents cases in which dykes failed because of low shear strength. Failure at the back slope at the land side occurred and large settlement of dykes was observed in the case of c≒0 and ϕ =22.5° (see Fig. 3(a) as well), where the maximum shear strain exceeds 2%.

Table 3 Mechanical conditions for dyke stability

Case	*c* (kPa)	ϕ (deg)	*G* (MPa)	Stability
Base case	0	22.5	5.76	Failure
c (kPa)	>10	-	-	Stable
ϕ (deg)	-	>25.0		Stable
G (MPa)	-	-	>11.5	Stable

However, no failure occurs in the cases of *c* and ϕ beyond 10 kPa and 22.5°, respectively (see Fig. 3 (b)). Because increased cohesion such as this is independent of depth, it is effective to prevent failure at the dyke surface, as portrayed in Fig. 3. This result suggests that even a small degree of increased cohesion using soil improvement with a small amount of cement addition contributes to sufficient stability of dykes.

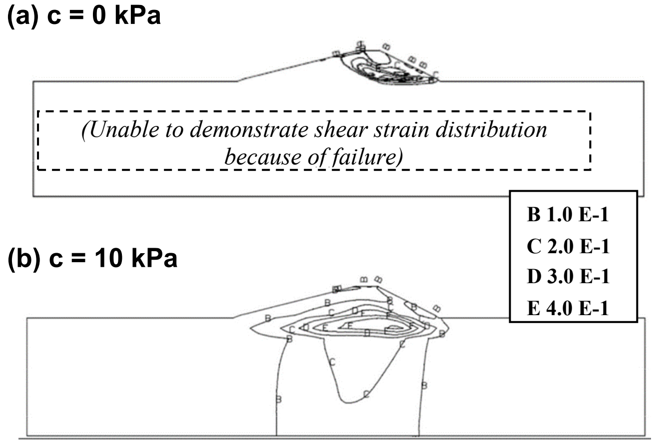


Figure 3 Influence of cohesion on dyke stability

To secure dyke stability, the results stated above indicate the following:

i) the internal frictional angle, ϕ, is increased by well compaction at the deep layer; and

ii) cohesion, *c*, is increased by addition of a small amount of cementing materials to the shallow layer of dykes.

5.3 Effects of Water-Level Rise (WLR)

In evaluation of the effects of rising water level for the short-term from the present height to the top of dykes, it is assumed that the weight of seawater is applied vertically and horizontally to the slope surface under the assumption that no seepage takes place in the dyke body.

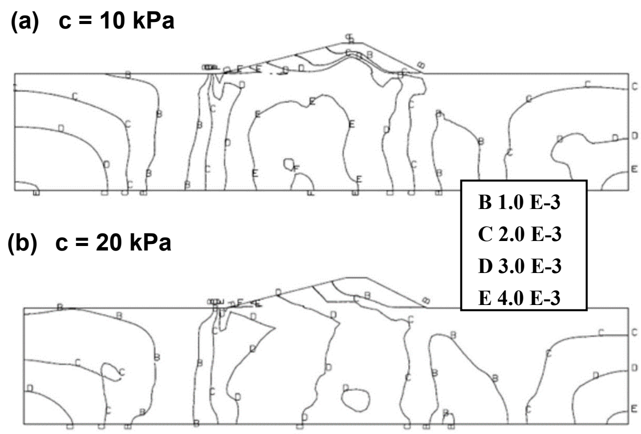
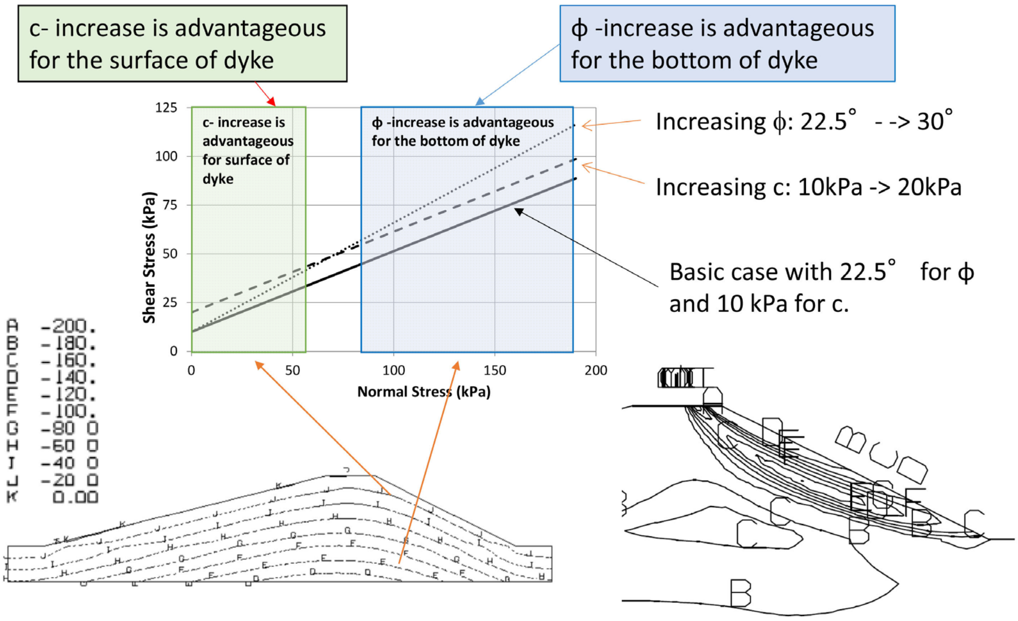


Figure 4 Influence of cohesion on incremental shear strain in dykes

As an example as is shown in Fig. 4, analysis is conducted by assuming *c*=10 kPa and 20 kPa. The following results were recognized in Fig. 4.

i) The dyke is pushed in the land direction. Then large shear stress is produced at the slope toe.

ii) The incremental principal strain line appears in the manner which traverses from the top of dykes at the river side to the toe of dykes at the land side, but no failure was observed in the dyke.



(a) Vertical stress

(b) Principal shear strain

Figure 5 Contribution of cohesion and friction to dyke stability.

6. HYBRID IMPROVEMENT FOR DYKE STABILIZATION

By referring to Fig. 5, the principle presented above and findings from numerical experiments described in previous sections show that dyke stabilization requires the increased cohesion which is the most important contributing factor for increased stability of dykes affected by water-level rise (WLR). Results imply that adaptive measures such as the addition of dyke soils to cement or mixtures increases the stability of dykes undergoing WLR. Conclusively, frictional force can be increased by compaction at the bottom and cohesion at the top of dykes, which are expected to stabilize whole the dykes.

7. CONCLUSION

Numerical experiments for the modeled sandy dyke founded on two-layered subsoils were conducted based on total stress analysis with consideration of the influences of unit weight, rigidity, internal friction, and cohesion of dykes on dyke stability. Results of a parametric evaluation demonstrate that increased cohesion is the most important contributing factor for increased stability of sandy soil dykes undergoing water-level rise (WLR). Results imply, from a practical perspective, that such adaptive measures as adequate compaction of dyke soils at the deep layer and addition of even a small amount of cement to the shallow layer increase the stability of dykes undergoing WLR in the context of climate change.

Therefore, it is strongly suggested to the government to adopt such an additional measure to improve the dyke resistance against the coming severe weather although the present conventionally used manual for river dyke construction in Japan should not add any materials except geo-materials.

ACKNOWLEDGMENTS

This research was supported by a Grant-in-Aid for Scientific Research from MEXT (FY2014–FY2017, Project No. 2681055), Japan.

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