Influence of Rain and Evaporation of the Stress State for Embankment with Soil/Water/Air Coupled F.E. Analysis

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Embankments are constructed with compacting soil with the aim of improving their stability and deformation characteristics. Typhoons and guerrilla rainstorms are occurring frequently due to the abnormal weather of recent years, and there have been many reports of cases of collapses of embankments due to their effects. Drainage measures for embankments against rainfall are different during construction and after commencement of use, and the effects are sustained intermittently from the start of construction to after the commencement of use. In this study, soil/water/air-coupled F.E. analysis was used to perform analyses of embankments which take into account compaction and the history of rainfall/evaporation. Further, changes in the stresses inside the embankment by the effects of rainfall sustained after commencement of use are considered.

1. Introduction

In the area of civil engineering structure evaluation criteria, performance-based design methodology, in which meeting the applicable performance requirements is essential, has come into the mainstream. Accordingly, in embankment engineering, the introduction of performance-based design has been a subject of discussion, and its framework has already been introduced into the field. Embankment structures are made up of compacted earth in order to improve stability and deformation properties. However, existing reports present many cases of collapsed embankment structures that fail due to typhoon-driven torrential rains, which have frequently occurred in recent years. For example, in 2011 Typhoon Nos. 12 and 15 hit the southern part of the Kii Peninsula. These typhoons caused landslides on National Highways 168 and 425, as well as embankment failures that resulted in road collapses. The stability of embankment against heavy rains depends strongly on four factors: treatment of foundation ground, quality of embankment materials, degree of compaction, and handling of water. Specifically, embankments often collapse due to drainage problems. In principle, embankments are provided with suitable drainage techniques according to specific land features and environmental conditions. Nonetheless, many
embankment failures have been reported. This fact suggests the involvement of one more factor, which is engineers' dependence on "rules of thumb" in carrying out embankment work, maintenance, and management. Consequently, in light of torrential rains seen in recent years, the present embankment guidelines may not provide proper drainage techniques for removal of water from embankment or sufficient maintenance and management considerations.

To evaluate an embankment with conventional embankment design methodology, conducting rotational slip analyses using rainwater infiltration analysis results is required. In this method, deformation analyses are usually omitted and water permeation analyses are conducted separately from stability analyses. However, infiltration and deformation problems are coupled with each other. Because of this, the present embankment evaluation technique is inadequate. Incidentally, existing studies (Oka et al\textsuperscript{10}, Kohgo et al\textsuperscript{11}, and Tanaka et al\textsuperscript{12}) examine stress conditions in embankment using their respective analysis techniques based on the mixture theory and the porosity theory.

This paper presents embankment analyses using the unsaturated soil/water/air coupled F.E analysis program (DACSAR-MP\textsuperscript{13}), which takes into account compaction, as well as rainfall and evaporation history. Specifically, changes in embankment stress behavior are analyzed with focus on rainfall during embankment structure construction and in-service periods. The mechanism of embankment collapse caused by torrential rain is also examined.

2. Mathematical model used for analysis

Here, the constitutive model for unsaturated soil and the soil-water retention characteristic curve (SWRCC) model are introduced.

2.1 Constitutive model for unsaturated soil applied the effective degree of saturation

Some constitutive models for unsaturated soil have been proposed since Bishop\textsuperscript{14} (1960) expressed the effective stress for unsaturated soils. Ohno et al\textsuperscript{15} (2007) expressed changes in stiffness of unsaturated soil with effective degree of saturation. In this model, application of the soil-water retention characteristic curve model can be used independent of the constitutive model. First, effective stress is expressed as follows:

\[ \sigma' = \sigma'' + p_1 \]  \hspace{1cm} (1)

where \[ \sigma'' = \sigma - p_a 1, \quad p_e = s S_e \]  \hspace{1cm} (2)

\[ s = p_a - p_e, \quad S_e = \frac{s - S_{re}}{1 - S_{re}} \]  \hspace{1cm} (3)

Here, \( \sigma' \) is effective stress tensor for unsaturated soil, \( \sigma'' \) is the net stress tensor, \( 1 \) is the second rank unit tensor, \( \sigma \) is total stress tensor, \( s \) is suction, \( p_s \) is suction stress, \( p_a \) is pore-air pressure, \( p_w \) is pore-water pressure, \( S_e \) is degree of saturation, \( S_{re} \) is effective degree of saturation, and \( S_{re} \) is degree of saturation at \( s \rightarrow \infty \). Volume change of soil at certain water content levels is expressed as:
The Stress State for Embankment with F.E. Analysis

\[ e = e_0 - \lambda \ln \frac{p'}{\zeta p'_{sat}} \]  \hspace{1cm} (4)

where \[ \zeta = \exp \left[ (1-S_c)^n \ln a \right] \]  \hspace{1cm} (5)

Here, \( p' \) is the mean principal effective stress, \( p'_{sat} \) is the yield stress at saturation, \( a \) and \( n \) are the fitting parameter to express the increase in consolidation yield stress according to de-saturation. The plastic volumetric strain is expressed as follows:

\[ e_p^p = \frac{\lambda - \kappa}{1+e_0} \frac{p'}{\zeta p'_{sat}} \]  \hspace{1cm} (6)

The consolidation yield stress can be obtained from equation (6) as shown in the following equation:

\[ p^p_c = \zeta p_{sat} \exp \left( \frac{\sigma_p^p}{MD} \right) \]  \hspace{1cm} (7)

where \[ MD = \frac{\lambda - \kappa}{1+e_0} \]  \hspace{1cm} (8)

Here, \( p^p_c \) is the yield stress represented by mean effective principal stress, \( M \) is \( q/p' \) at the critical state, and \( D \) is the dilatancy coefficient. The following yield function can be obtained by applying equation (7) to the original Cam clay model.

\[ f\left( \sigma', \zeta, e^p_p \right) = MD \ln \frac{p'}{\zeta p_{sat}} + D \frac{q}{p'} - e^p_p = 0 \]  \hspace{1cm} (9)

where \[ p' = \frac{1}{3} \text{tr} \sigma', \quad q = \sqrt{\frac{3}{2}} : s, \quad s = \sigma' - p' I = A : \sigma', \quad A = I - \frac{1}{3} \otimes I \]  \hspace{1cm} (10)

Here, \( I \) is the fourth rank unit tensor. Equation (9) reduces to the original Cam clay model under saturated condition \((S_c = 1)\). Fig.1 shows the concept of yield surface expressed by equation (9).

3. SWRCC model considering hysteresis

Soil-water retention characteristic curve (SWRCC) expresses the relationship between suction and soil moisture. It strongly depends on suction history and SWRCC on wetting process does not correspond to that

![Fig.1 Yield surface for unsaturated soil](image-url)
on the drying process. There are innumerable scanning curves. Kawai et al.\(^7\) proposed a SWRCC model which can express hysteresis, with application of similarity appearing for both the drying and wetting processes, respectively (Fig.2).

![Graphs showing drying and wetting processes](image)

Fig.2 SWRCC model proposed by Kawai et al.

4. Embankment stress changes based on rainfall and evaporation history

The analyses presented in this paper take into account compaction, as well as a rainfall and evaporation history, during embankment construction and under various intermittent rainfall and evaporation conditions that take place after service commencement. A drainage layer provided inside embankment (1) and installation of vegetation mats on slope (2) are simulated in the analyses as embankment drainage techniques. Using stress distributions that would take place one year after service commencement, this paper also examines the impact of rainfall occurring after the embankment comes into service.

4.1 Conventional drainage technique

The following is an example of drainage technique commonly used in embankments.

Horizontal drainage layers are inserted into the embankment at constant thickness intervals on an as needed basis to remove water infiltrating the embankment, as shown in Fig.3. It is especially necessary to provide horizontal drainage layers in a high embankment with a large slope face, in a cutting and embankment slope, at the boundary between cut ground and embankment, in a fill on a mountain stream, and in a fill on sloping ground. Additionally, when soil of high moisture content is used to construct a high embankment, highly permeable materials are used to provide horizontal drainage layers. These materials are used to reduce pore pressure and improve embankment stability, since increased pore pressure in the embankment can result in bulging or collapse of the slope face.

![Diagram of drainage layer](image)

Fig.3 Drainage layer
4.2 Simulation of average rainfall in Japan

4.2.1 Analysis conditions

Fig. 4 shows moisture characteristic curves used for the analysis. Table 1 shows material constants, determined using data obtained from indoor experiments. Here, \( m \) is Mualem's modulus.

Fig. 5 shows the analyzed embankment and its analysis range. The drainage techniques considered in this analysis were a drainage layer 3m in length and 0.6m in thickness (water permeability coefficient: 0.1 m/day) at the toe of the slope and vegetation mats on the slope face. Parameters were set on the drainage layer under conditions in line with the embankment earthwork guidelines. The evaporation rate of the vegetation mats was calculated based on commonly used seeds.

<table>
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<th>( \lambda )</th>
<th>( \kappa )</th>
<th>( M )</th>
<th>( m )</th>
<th>( S_{r,0} )</th>
<th>( k_s(m/day) )</th>
<th>( p'_{wp}(kPa) )</th>
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<td>( n )</td>
<td>( \epsilon_b )</td>
<td>( a )</td>
<td>( \nu )</td>
<td>( G_s )</td>
<td>( k_s(m/day) )</td>
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<tr>
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<td>10</td>
<td>0.33</td>
<td>2.7</td>
<td>0.01</td>
<td></td>
</tr>
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</table>

\( m \) : Mualem's modulus

Fig. 4 Water characteristic curve

Fig. 5 Mesh and boundary condition for analysis

Fig. 6 shows the history of rainfall and evaporation used in this section. To simulate the average rainfall in Japan (1700mm), the annual 2011 rainfall for Kyoto City in Kyoto Prefecture (1650mm) was used, assuming similarity in total rainfall. Similarly, Kyoto City in Kyoto Prefecture annual evaporation data was used to simulate average evaporation in Japan. Fig. 7 shows rainfall and evaporation conditions. Rainfall was converted to an hourly flow
rate, which was assigned to the top and slope of the embankment. A rainfall of 137.5mm, derived as single-month rainfall from the annual rainfall of 1650mm, was allotted to the period of embankment construction. For the subsequent one-year in-service period in the analysis, rainfall was simulated on a monthly basis using the one-year rainfall history taken in Kyoto Prefecture.

4.2.2 Analysis results

Fig. 8 shows analysis results arranged into data from a) immediately after construction, b) 6 months after construction, and c) 12 months after construction and compiled as to the mean effective principal stress, deviator stress, suction, saturation, and critical stress ratio parameters.

Fig. 8 (a) reveals that the mean effective principal stress gradually increases on the surfaces of and inside the embankment due to one-year rainfall at points a) immediately after construction, b) 6 months after construction, and c) 12 months after construction. It is, however, important to note that the mean effective principal stress is substantially lower in the proximity of the toe of the slope (drainage layer) than in the inner part of the embankment. A conceivable reason for the lower values is the presence of gradual infiltration flows from the inner part of the embankment toward the drainage layer that occur during construction and after service commencement.

Fig. 8 (b) shows that the deviator stress increases in the inner part of the embankment with time in comparison to a) immediately after construction, due to self-weight consolidation effects resulting from rainfall. The figure also reveals increases in deviator stress on embankment surfaces, though to a lesser degree.

Fig. 8 (c) reveals a decrease in the suction at b) 6 months after construction, due to the effects of the rainy season and, and at c) 12 months after construction, to a level more or less the same as the initial level.

Fig. 8 (d) shows that the saturation, as compared with data at a) immediately after construction, gradually

![Graphs showing analysis results of Average rainfall in Japan](image-url)
decreases until c) 12 months after construction. This decrease in saturation begins first at the top of the embankment, as the moisture inside the embankment flows to the drainage layer with the passage of time.

Fig.8 (e) indicates that the critical stress ratio is slightly higher at the toe of the slope (drainage layer) than in other parts of the embankment. A conceivable reason for this higher critical stress ratio is that the mean effective principal stress is low in the drainage layer region, as shown in Fig.8 (a). However, no failure is recognized in any part of the embankment. Moreover, the critical stress ratio was higher in June than immediately after embankment construction, due to rainfall; although, it showed a stabilizing tendency towards December. These results suggest that, under the average rainfall in Japan, embankments increase in strength and tend to stabilize as a result of self-weight consolidation effects brought about by rainwater infiltration.

4.3 Simulation of torrential rainfall

4.3.1 Analysis conditions

For the purpose of this analysis, the material constants, water characteristic curves, and analyzed embankment (Table 1, Fig.4 and Fig.5) used in the aforementioned analysis are used.

Fig.9 shows the rainfall history used in this analysis. To simulate the torrential rainfall seen in recent years, the 2011 annual rainfall data (5370mm) taken in Higashimuro County of Wakayama Prefecture was selected. It should be noted that the total rainfall in the rainy season (May and June) of 1100mm is characteristically high as compared with the aforementioned rainfall history of Kyoto Prefecture. Incidentally, in 2011, Japan was hit by one typhoon in July (Typhoon No.6) and two typhoons in September (Typhoon Nos.12 and 15). These typhoons unleashed torrential rainfall in the Kii Peninsula.

4.3.2 Analysis results

Fig.10 shows analysis results arranged into data from a) 1 month after construction, b) 3 months after construction, and c) 7 months after construction and compiled as to the mean effective principal stress, deviator stress, suction, saturation, and critical stress ratio parameters.

Fig.10 (a) shows that the mean effective principal stress stays more or less at the same level at a) 1 month after construction and b) 3 months after construction, while at c) 7 months after construction, the mean effective principal stress exhibits a decreasing trend from the toe of the slope (drainage layer) along the slope face. This is considered to result from the insufficient drainage capacity of the embankment to handle the cumulative rainfall in May and June, totaling 1100mm, and the torrential rain caused by the July typhoon, totaling 1000mm rainfall, which causes saturation beginning at the toe of the slope.

Fig.10 (b), representing the deviator stress, suggests that the inner part of the embankment increases in strength with time from a) 1 month after construction, due to self-weight consolidation effects by virtue of rainwater infiltration. However, the deviator stress on the embankment surfaces, on the whole, stays more or less at the same level and is lower than that in the inner part of the embankment.
Fig.10 (c) and (d) show that both suction and saturation are affected by rainfall. This is especially true at c) 7 months after construction, when the embankment has been subjected to a rainfall of approximately 1100mm, the drainage layer has lost it functionality, the inner part the embankment is almost saturated, and as a result, the suction is absent.

Suggesting a cause of the failed toe of the slope, Fig.10 (e), which represents the void ratio, provides evidence of the occurrence of a collapse phenomenon specific to unsaturated soils in the proximity of the toe of the slope.

Lastly, Fig.10 (f) shows that at c) 7 months after construction, the toe of the slope has failed after reaching its critical stress ratio. This occurs as a consequence of the decrease in the mean effective principal stress, as shown in Fig.10 (a).

These results show that the conventional drainage technique implemented in embankments would be ineffective against the torrential rains that fell in July 2011 in Higashimuro County of Wakayama Prefecture.

![Graphs showing stress and saturation changes](image)

5. Conclusions

This paper presented an embankment analysis using the soil/water/air coupled F.E. analysis program (DACSAR-MP), which took into account compaction, as well as rainfall and evaporation history, and provided an analytical representation of stress behaviors in the embankment as exhibited under various rainfall conditions during in-service periods. Subsequently, the mechanism of embankment collapses caused by torrential rain was examined; the suitability of the conventional drainage technique for embankment structures was investigated; the conventional drainage technique was reviewed; and improvements to the conventional technique in the future were proposed.
The following findings were identified through the present study:

- Under average rainfall conditions or the natural environment in Japan, embankments are predicted to increase in strength due to self-weight consolidation effects brought about by rainwater infiltration and are expected to eventually become stable.

It is believed that the accuracy of qualitative evaluations will increase in the future by using the actual and specific soil properties of materials used in embankments and in simulating construction processes.

REFERENCES


