A case study of long- and short-term hydraulic state changes in embankment in Hokkaido

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ABSTRACT

Mechanical stability of embankments such as road embankments and river dykes is significantly influenced by their internal hydraulic states, as represented by phreatic surface location and pore water pressure distribution. The mass transfer across the embankment surfaces through water infiltration and evapotranspiration, and the internal migration of pore water to/from foundation soil layers are considered to play a major role in dictating the evolution of the hydraulic state. This paper reports a case study in which hydraulic state variations in an embankment in Hokkaido were monitored over 9 months, including a winter period with ground surface freezing and a significant snow cover. The studied embankment was relatively new, constructed with artificially mixed clay and sand which were generated by nearby excavation. The monitoring records indicate a consistent trend of under-drainage to the foundation layer all during the 9 months, with the pore water pressure at deeper parts registering minimum values during winter and reaching maxima during summer. Explanations for this and other observed features were sought by performing unsteady unsaturated seepage flow analysis with some assumed surface input models. Although the adopted models are fairly crude, the analysis results offer important insights into factors that govern the hydraulic state of low-permeability embankment in snowy cold regions.

Keywords: embankment, seepage, ground water, rainfall, slope stability

1 INTRODUCTION

Evaluation of embankment instability, triggered by intense rainfalls, earthquakes or flooding is commonly conducted by either coupled or uncoupled analysis of seepage and force equilibrium. In performing the analysis, or in judging the general conditions of embankment, it is important to understand the quasi-equilibrium (i.e. equilibrium with longer-term, slower events such seasonal weather changes) hydraulic states in the embankment before such short-term events, as the consequences will be dependent on the initial conditions. In a long-standing embankment, the quasi-equilibrium state is expected to be governed by climatic conditions, embankment soils, surface characteristic and foundation layer conditions. Establishing a general, broad relationship between these environmental factors and embankments’ long-term responses will lead to a useful guide in assessing the general state of pore water pressure and hence the mechanical stability of embankments from rather limited information sources such as soil layering and weather data.

Existing studies on mass transfer problems in slopes seem to focus more on short-term responses such as against a single rainfall event (e.g. Ng and Zhan, 2007). A more limited number of geotechnical studies considered the problem in longer time spans. For example, Smethurst et al. (2006) and Heppell et al. (2014) report monitoring of seasonal hydraulic conditions in a London Clay cut slope, proposing a semi-theoretical model of mass transfer considering evapotranspiration effects. The first author (Nishimura, 2015) simulated full time-series responses of phreatic surface elevations in a gravelly sand river dyke by unsaturated seepage flow analysis using rainfall data. In the highly permeable coarse-grained dyke, the observed phreatic surface was reproduced satisfactorily without considering evapotranspiration processes. Whether a similar approach works for less permeable embankments remains to be investigated.

This paper reports monitoring results of the hydraulic states in an embankment in Hokkaido, Japan. In this snowy cold region, the ground surface processes during winter, such as soil freezing and snow covering further complicate the problem. Insights into the
short-term and long-term responses of the hydraulic states are discussed based on the monitoring records and seepage analysis performed with some hypothetical boundary and material conditions.

2 SITE AND SOIL DESCRIPTIONS

2.1 Site and embankment

The studied embankment is located in Naganuma Town, in a floodplain along Chitose River, Hokkaido, Japan. The monitoring station was some 15km north of New Chitose Airport. Fig. 1 illustrates the cross-section of the embankment. The ground condition is relatively uniform along the embankment; the original ground consists of a thin (2-3m) Alluvial clay surface layer, immediately underlain by a thicker volcanic sand layer. The embankment has a height of 5.7m with a slope of 1:4 on both sides. It was constructed in multiple stages, with the height added by 1.4m in 2010, 2.6m in 2011 and 1.7m in 2013. Probably because the clay layer was thin, the embankment suffered little subsidence after construction. The slope surface was grass-covered, also growing other short plants such as white clover, as shown in Fig. 2. This part of Hokkaido is characterised by relatively small amount of snow during winter, with the snow cover normally not exceeding 700mm at maximum. This instead leads to greater frost penetration.

2.2 Soil properties

The embankment soil was locally procured by mixing the same Alluvial clay and the volcanic sand, which occurred as surplus soil in nearby excavation. The clay was soft at high water contents (50-70%) and was inappropriate for embankment as it is. Mixing the two soils at approximately 1:1 ratio by weight reduced the water content closer to the optimum water content of the mixed soil, as shown in Fig. 3. The mixed soil consequently has significant amount of clay, and its permeability was very low. A constant-rate-of-strain consolidation test on a specimen re-compact in laboratory suggested the coefficient of permeability, k, at saturated states smaller than \(10^{-8}\) m/sec, decreasing further under higher effective stresses (>100kPa) to \(10^{-9}\) m/sec, a value close to that of the alluvial clay that constitutes half of the mixture and underlies the embankment. The physical properties of the soils are shown in Table 1, while the strength characteristics are briefly reported by Panta and Nishimura (2015).

![Fig. 1. Cross-section of embankment and instrumentation.](image)

![Fig. 2. Surface conditions of embankment; (a) Overall view (b) 15 Oct 2014 (c) 27 Feb 2015 (d) 2 Apr 2015.](image)

![Fig. 3. Gradation and compaction curves of embankment soil (newly compacted in laboratory by using fresh mixture).](image)

Table 1. Physical properties of soils.

| Soils          | Field water content* | \(w_p\) (%) | \(w_z\) (%) | \(\rho_s\) (g/cm³) | Fines content** |
|----------------|----------------------|-------------|-------------|-------------------|-----------------|
| Embankment     | 19.5-30.0            | 30          | 49          | 2.71              | 54              |
| Alluvial clay  | 48.0-68.1            | 32          | 75          | 2.74              | 82              |

*As of 18 Aug 2014  ** Smaller than 0.075mm

2.3 Instrumentation

The monitoring was initiated on 19 August 2014 and is continuing to the present. The configuration of instrumentation is illustrated in Fig. 1. The pore water pressure was measured by UNSUC tensiometers (CHG...
—2100AET), while the volumetric water content and temperature were measured by Decagon 5TM sensors at different depths from the mid-slope. Above the surface, rainfall, relative humidity and air temperature were measured. The snow cover thickness during the winter was evaluated from images of a vertical scale stick taken by a fixed-point interval digital camera. Lens frosting and sporadic disorientation of the camera by blizzards led to lacks of data for some short periods.

At the slope toe, a well was installed to monitor the ground water level. Unfortunately, the well was inadvertently buried by a contractor after 90 days of monitoring. Another well, installed at some 200m from the toe in the opposite side, provided past records. It indicated that the ground water level in the foundation layers was stable at -1.5 to -2.0m over at least 5 years, with an annual fluctuation of 0.3-0.4m.

3 MONITORING RECORDS AND INTERPRETATION

3.1 Climatic events and ground thermal responses during monitoring period

The measured precipitation and snow cover thickness are shown in Fig. 4 (top). The shown precipitation data are those simply recorded by the rain gauge, and do not necessarily capture the correct amount and timing of precipitation during winter, when it took form of snow. The monitored period (Aug 2014 - May 2015) can be divided into four phases; (i) August to November and mid-March to May, which can be broadly defined as summer, (ii) December to early January, when the ground surface freezes, (iii) January to February, when the ground surface temperature stays exactly at 0°C under a continuous snow cover and (iv) early March, when the snow melts over the ground surface that was warmed above the freezing temperature. As shown in Fig. 4, the snow cover data from nearest AMeDAS weather station (Chitose, 15km away from the study site) agrees well with those from the site. Where the latter is missing, the former can be referred to. The rainfall on 11 Sep 2014 (69mm/day) was associated to the largest rainfalls in the record in this region, with some localities recording more than 200mm/day. A line-shaped rainband, an increasingly common cause of such intense rainfall events in Hokkaido (e.g. Yamada et al., 2012), was formed, but the study site was slightly off the rainband centre and less directly affected. Rainfalls of comparable intensity were observed in this site on 12 Jun (72mm/day; the data before the monitoring period was taken from AMeDAS) and on 18 Aug (59mm/day) in the same year. The average annual precipitation at Chitose station during 2010-2014 is 1017mm.

During Phase (iii), there is no clear evidence to judge whether the ground surface was frozen or not, as the temperature at 0.05m depth was consistently 0.0°C. The abnormally small values of electric conductivity registered by the moisture sensor during the same period (see Fig.4 bottom) may be indicative of partial freezing. In order to reproduce the observed pore water pressure variations, however, the analysis described later needed to hypothesise that the ground surface was at least partially unfrozen and the snow is gradually melted from the bottom to supply liquid water to the ground. At any stage, no significant pore pressure depression associated with frost heave was observed.

3.2 Pore water pressure responses

The measured pore water pressure was displayed as time-series at each monitored depth in Fig. 4 and as snapshots of profiles in Fig.5. Over the whole period (Fig. 5 left), the pore water pressure distribution suggested continuous under-drainage, with the pressure at deeper locations significantly lower than expected from a hydrostatic line projected from the embankment surface. Fig. 4 indicates that this distribution is annually cyclic and stable in long-term, not showing tendency to approach the hydrostatic state. While the offset accuracy of the deeper sensors needs a check at the end of monitoring, this apparent under-drainage is qualitatively explained by the foundation stratigraphy.
As stated earlier, the original, natural ground water table exists at 1.5-2.0 m below the original surface (i.e. the top of the Alluvial clay). As illustrated in Fig. 6, then, the pore water pressure at the bottom the clay layer is stably fixed at 5-15 kPa (0.5-1.5 m head). The pressure profile in the embankment depends on the relative magnitudes of permeability of the layers between the two fixed pressure points (the embankment surface and the Alluvial clay bottom). Fig. 6 illustrates two example scenarios of permeability variations.

While the pore water pressure reacted sharply against the rainfall events at 0.45 m depth, and less sharply at 1 m depth, the deeper locations exhibited only long-term fluctuations (Fig. 4 and Fig. 5 right). The pressure at -1 m depth started increasing in early January, and that at -2 m and -3 m depth followed it with delays. An interesting fact is that the timing coincided with the beginning of continuous snow cover (i.e. Phase (iii) in Fig. 4). This fact, together with the stable temperature record of 0.0°C at the ground surface, may suggest that the melted water is continuously supplied at the surface, as the geothermal flux melts the snow cover base. This possibility of water supply under a snow cover needs more detailed investigation in future.

4 SIMULATION OF PORE WATER PRESSURE CHANGES BY SEEPAGE ANALYSIS

4.1 Analytical model and conditions

Finite element analysis was performed to investigate whether an unsteady unsaturated seepage flow model is capable of reproducing the short-term and long-term responses of the embankment under the given climatic conditions. Another intention of the analysis was to explore possible conditions of the embankment and surface processes based on back calculation and obtain general insights into infiltration modelling. The analysis was formulated based on Richard’s equation (e.g. Nguyen et al., 2014) with the pressure head, \( \psi \), as unknown variables. The unsaturated hydraulic characteristics are represented by a soil water characteristics curve (SWCC), \( \theta_s(\psi) \), and a relative permeability function, \( k_r(\psi) \). The latter is a factor to reduce the saturated coefficient of permeability, \( k_{sat} \), for unsaturated states. The compressibility of soils at saturated states is expressed by the specific storage coefficient, \( S_v \) (equivalent to \( m_v/\gamma_v \), where \( m_v \) is the coefficient of volume compressibility and \( \gamma_v \) is the unit weight of water).

![Fig. 7. Finite element modelling of embankment.](image)

**Table 2. Input parameter values adopted in the reported analysis.**

| Layer | \( k_{sat} \) (m/sec) | \( m_v \) (m^3/kN) |
|-------|----------------------|------------------|
| Bk-u  | \( 5 \times 10^{-7} \) | 0.05             |
| Bk-l  | \( 1 \times 10^{-6} \) | 0.05             |
| Ac    | \( 5 \times 10^{-9} \) | 0.05             |
| Sp    | \( 1 \times 10^{-6} \) | 0.001            |

**Fig. 8. Adopted soil water characteristics curve and relative permeability function.**
The modelled cross-section is shown in Fig. 7 with idealised material grouping. After many trial analysis runs, the top 0.5m layer of the embankment was considered to have properties different from the deeper domain to explain the observed results. At the monitored site, the maximum frost depth reaches 0.5-0.8m in some years. Along with the plant root actions, it is plausible that the top layer has undergone significant loosening for the 3 years since 2011, when the surface was completed (see Section 3.1).

A comprehensive suite of parametric runs was performed with a variety of input value combinations. This paper reports only a selected case which appeared to capture the observed behaviour most appropriately. The input parameter values are summarised in Table 2. The adopted SWCC and the relative permeability curve are shown in Fig. 8. These curves are based on those recommended for clayey soils in Japanese engineering guideline for river dykes. The SWCC was shifted along the \( \theta_s \) axis to be compared with the experimental data. This apparent shift is immaterial to the analysis, which uses only the slope of the SWCC. The grey-shaded area in Fig. 8 is the range which was eventually relevant to the analysis. For this limited area, the adopted curve is a good representation of the drying curve, although the hysteresis was not considered in this study. The adopted \( k_r \) curve assumes a relatively large residual value at high suctions compared to other commonly used models such as the van Genuchten (1980) model.

The imposed boundary conditions are, (i) no flux across the two lateral boundaries, (ii) constant pressure at 392kPa along the bottom boundary and (iii) infiltration and evapotranspiration along the surface boundary. The infiltration involved imposing incoming flux corresponding to the rainfall during summer (i.e. Phase (i) shown in Fig. 4). When the surface pore water pressure reached zero, the condition was automatically switched to imposing zero pore pressure to avoid unnatural forced infiltration. The adopted evapotranspiration model was a tentative and fairly simplistic one which assumed a linear relationship between the outgoing flux and the effective degree of saturation at the surface nodes:

\[
f_{e\alpha} = \alpha (\theta_{w} - \theta_{s})/(\theta_{s} - \theta_{w})
\]

where \( f_{e\alpha} \) is the evapotranspiration flux (mm/hour), \( \theta_w \) is the volumetric water content, and \( \theta_{w} \) and \( \theta_{s} \) are its values at saturated and residual states, respectively. The coefficient \( \alpha \) was determined as 0.23 mm/hour by fitting the computed results against the observed response at 0.45m depth during the dry periods in the summer. During Phase (ii), when the ground surface was largely frozen, no flux was allowed across the surface. Based on the earlier observation, a continuous supply of water was assumed during Phases (iii) and (iv) by setting zero pore pressure at the surface.

The initial condition was set hydrostatic. However, the May 2014-May 2015 conditions (the missing data for May-Aug 2014 were substituted by AMeDAS data) were repeated 5 times (i.e. 5 imaginary years) before Aug 2014, from which the comparison between the monitoring and analysis results is to be considered. After these initial imaginary years, the computed hydraulic state reached inter-year equilibrium with the input climate conditions.

4.2 Simulated pore water pressure responses and insights from parametric runs

The simulated pore water pressure responses from a representative case, run with the inputs shown in Table 2, are shown in Fig. 9 as time-series and Fig. 10 as profiles. Comparing these with the observed results shown in Figs. 4 and 5, respectively, the responses at shallower locations (0.5m and 1m depth) are well reproduced, although the assumption of continuous surface water supply under the snow cover during Phases (iii) and (iv) seems to have led to an excessive supply, leading to an abrupt jump to a hydrostatic ceiling at the beginning of Phase (iii). Further study is necessary to model the potentially gradual manner in which the geothermal flux melts the snow cover bottom. The simulated responses at deeper locations (2m and 3m depth) showed much smaller annual variations than observed at the site, although the delayed pressure increases after Phase (iii) were qualitatively reproduced. The parametric runs indicated that the pore water pressure behaviour at these depth is almost exclusively governed by the bottom boundary condition. With the fixed pressure at the bottom in the analysis, the computed annual pressure variations were minimal. An improvement in the simulation will be possible by imposing a bottom boundary condition that corresponds to measured ground water level in the Sp layer. To make a prediction based solely on climatic inputs, however, understanding and modelling larger-domain processes that affects the pore water behaviour in Sp layer will be necessary.

![Fig. 9. Simulated time-series of pore water pressure for 4 points along vertical line from the mid-slope.](image-url)
The simulated response against the intense rainfall on 11 Sep 2014, shown in Fig.10 right, agreed well with that observed at shallower locations. However, such an agreement was made possible only if the significantly larger k value was assumed for the surface layer. Such a loosening of the surface is plausible as discussed earlier, but the quantitative assessment of its effect requires more study. It should be noted that the k value of $5 \times 10^{-8}$ m/sec is justifiable for the deeper, as-compacted part, if even the general difference seen between laboratory and field permeability measurements is taken into account. In addition, assigning a larger k value to the whole embankment would not simulate the delayed responses at the deeper locations as seen in Figs.4 and 9.

5 CONCLUSIONS

This paper reported an ongoing investigation into the short- and long-term hydraulic state variations in an embankment in Hokkaido. The case study was reported based on 9-month monitoring records of pore water pressure, climatic conditions, etc. and simulation of water transfer by unsteady unsaturated seepage flow analysis. The period included a winter that involved ground freezing and snow covering. Although the study is still in progress and crude assumptions were made on the surface input models and soil parameters, tentative but important insights were obtained as below.

(a) Due to the low permeability ($k < 10^{-8}$ m/sec) of the embankment soil, a soil prepared by mixing Alluvial soft clay and volcanic sand, the depth below 1m exhibited only seasonal pore water pressure variations, while the shallower layers reacted sharply to short-term events such as intense rainfalls.

(b) A comprehensive parametric study with the seepage analysis, though not reported fully in this paper, indicated that the above reactions cannot be reproduced if a uniform value of the coefficient of permeability, k, is assumed. A significantly larger k value, perhaps due to plant root actions and freeze-thaw repetitions, near the surface needed to be assumed to output more realistic pore water pressure responses.

(c) The recorded pore water distribution indicated consistent under-drainage all across the year. This is probably caused by existence of a permeable volcanic sand layer beneath the 2-3m thick Alluvial clay foundation layer. The low permeability of the embankment body means the small pore water pressure applied at the bottom boundary propagate to shallower locations close to the embankment slope surface.

(d) Although an adopted evapotranspiration boundary model was obviously crude and needs future elaboration, it was useful in reproducing the inter-rain pore water pressure decreases in shallow layers. The future study will involve incorporating more climatic variables, such as temperature, insolation, etc.

(e) The observed trend of pore water pressure variations at the deeper locations within the embankment suggests that the water is likely to be provided from the snow cover bottom, as it is slowly melted by the ground heat.

Further monitoring and characterisation of soil properties will confirm or may modify some of these interpretations and tentative conclusions.

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