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Probability Assessment of Slope Instability in Seasonally Cold Regions under Climate Change

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13 **Abstract**

14 This paper proposes an effective approach for evaluating the influences of climate change on slope
15 stability in seasonally cold regions. Firstly, to semi-quantitatively assess the effects of climate
16 changes on the uncertainty of climate factors, this study analyzes the trend of the two main climate
17 factors (precipitation and air temperature) by the regression analysis using the meteorological
18 monitoring data of the past 120 years in different scales (e.g., world, country (Japan), and city
19 (Sapporo)), and the meteorological simulation data obtained by downscaling the outputs of three
20 different regional atmospheric models (RAMs) with lateral boundary conditions from three different
21 general circulation models (GCMs). Next, to discuss the effects of different climate factors (air
22 temperature, precipitation, etc.) and to determine the key climate factors on the slope instability, an
23 assessment approach for evaluating the effects of climate changes on slope instability is proposed
24 through the water content simulation and slope stability analysis using a 2-dimensional (2D) finite
25 element method (FEM) homogeneous conceptual slope model with considering freeze-thaw action.
26 Finally, to check the effectiveness of the above assessment approach, assessment of instability of an
27 actual highway embankment slope with the local layer geometry is done by applying the past and
28 predicted future climate data. The results indicate that affected by global warming, the air
29 temperature rise in some cold cities is more serious. The predicted future weather will affect the
30 shape of the normal density curve (NDC) of the distribution of slope failures in one year. The
31 climate changes (especially the increase in precipitation) in the future will increase the infiltration
32 during the Spring season. It will lengthen the time that the highway slope is in an unstable state due
33 to high volumetric water content, thereby enhancing the instability of the slopes and threatening
34 more slopes in the future.

35 *Keywords:* Climate change, Slope instability, Seasonally cold regions, Probability assessment,

36 Freeze-thaw action

37 **Introduction**

38 In the coldest month of the year, areas where the ground temperature is usually below 0 °C, are
39 defined as cold regions [1, 2], such as some high latitude regions, like Hokkaido, Japan. In the cold
40 regions, the climate factors (e.g., precipitation and air temperature) and their variations are
41 considered as the significant causes of slope failures or landslides [3, 4]. Therefore, many studies
42 have been done to discuss the failure mechanisms and trigger factors of slope failures in the cold
43 regions [5, 6]. Ishikawa et al. [7] described that there is a difference in the failure mechanism of
44 slopes between cold regions and warm-temperate regions due to additional factors, i.e., freeze-thaw
45 action. Accordingly, Ishikawa et al. [8] divided slope failures in cold regions into two main classes:
46 slope failures occur during the snow-melting season (March-April-May) and slope failures occur
47 during heavy rainfall season (August-September). Therefore, it is necessary to investigate the
48 influences of climate change on the slope stability in seasonally cold regions.

49 During the heavy rainfall season, the frequency of severe rainfall events is expected to increase in
50 many mountain areas as a consequence of the influence of global warming [9]. The rainfall
51 infiltration caused decrease in matrix suction is considered as a main cause of slope failures or
52 landslides [10-12]. For example, according to the statistical data surveyed by Japan Meteorological
53 Agency [13] for 1,000 locations in Japan, the annual average number of rainfall intensity greater
54 than 50 mm/h increased from 195 times (1987~1998) to 226 times (1999~2010). On the other hand,
55 with the intensification of global warming in the past few decades, during the snow-melting season,
56 the occurrences of geological disasters in seasonally cold regions are more frequently reported. For
57 example, surveyed by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT), in April,
58 the average number of geological disasters in Japan increased from about 50 times (2008~2012) to

59 near 100 times (2013~2017), almost doubled. While in August, this number increased from about
60 120 times (2008~2012) to near 240 times (2013~2017), also doubled. Therefore, the influences of
61 climate change on slope stability are intensifying. However, little attention is paid on the influences
62 of climate changes on slope failures in cold regions [11, 14, 15].

63 From the view of climate changes, many attempts were also made to assess the influences of
64 climate change on slope failures by exploiting downscaled synthetic future climate scenarios
65 obtained from the GCMs as an input of slope stability [9, 16, 17]. Chiang and Chang [9] pointed out
66 that the average annual maximum rainfall will have a 15.2% increase in 2010-2099 compared with
67 that in 1960-2008, and the average total unstable area will have a 12.8% increase in Taiwan.
68 Ciabatta et al. [17] employed the PRESSCA system (an operational early warning system) for
69 evaluating the influences of climate change on landslide hazard in the Umbria territory, Italy for
70 three different periods (1990-2013 (baseline), 2040-2069, and 2070-2099). They found that in the
71 future period, mainly during the winter season, a general increase (up to more than 40%) in
72 landslides occurrence is expected for the Umbria territory, Italy.

73 Accordingly, the objectives of this study are (1) to semi-quantitatively assess the effects of
74 climate changes on the uncertainty of climate factors, and (2) to discuss the influences of climate
75 changes on the occurrence of slope failure and its probability distribution. For these purposes, firstly,
76 this study analyzes the trend of the two main climate factors (precipitation and air temperature) by
77 the regression analysis using the meteorological monitoring data of the past 120 years in different
78 scales (e.g., world, country, and city), and the meteorological simulation data obtained by
79 downscaling the outputs of three different RAMs with lateral boundary conditions from three
80 different GCMs. Next, an assessment approach for evaluating the effects of climate changes on
81 slope instability is proposed through the water content simulation and slope stability analysis using

a 2-dimensional (2D) FEM homogeneous slope model with considering freeze-thaw action by applying two kinds of climate boundary conditions: meteorological monitoring data and meteorological analysis data. Among them, the meteorological monitoring data is searched from the Automatic Meteorological Data Acquisition System (AMeDAS). The meteorological analysis data is a reasonable predicted value of the future meteorology based on the regression analysis of the meteorological monitoring data of the past 120 years. Therefore, three kinds of climate data are used in this study, i.e., meteorological monitoring data, meteorological analysis data, and meteorological simulation data. The meteorological monitoring data is the direct monitoring data so it is more reliable. However, this kind of climate data is historical data so it can not be used in the future. The meteorological analysis data is the assumed future climate data that add the average changes in precipitation and air temperature from the regression analysis to the meteorological monitoring data. Therefore, this kind of climate data can be obtained very easily and quickly, while the differences of climate change in different seasons are not considered. The meteorological simulation data are obtained from GCMs. The differences of climate change in different seasons are considered, while this kind of data is more complex and difficult to obtain. Finally, to check the effectiveness of the above assessment approach, assessment of instability of an actual highway embankment slope with the local layer geometry is done by applying the past and predicted future climate data.

Slope stability assessment approach

Modelling freeze-thaw action and long-term moisture fluctuation

Slope failures in cold regions are usually subjected to freeze-thaw actions and rainfall and/or snowmelt water infiltration. Siva Subramanian et al. [18] proposed a slope stability assessment approach to simulate the long-term fluctuation of the moisture and factor of safety (FOS) for cold

105 region slopes based on non-isothermal seepage flow and limit equilibrium method (LEM) as shown
 106 in Fig. 1. In this assessment approach, the influences of freeze-thaw action and long-term moisture
 107 fluctuation on the slope stability are taken into consideration. Moreover, the rainfall and/or
 108 snowmelt water infiltration can be simulated. However, runoff is ignored as this assessment
 109 approach is established by using the 2D GeoStudio software [19].

110
 111 **Fig. 1.** Slope stability assessment approach (adapted from [18]).

112 Modelling atmosphere-ground interactions

113 The mass balance equation could be used for calculating the water flux on the ground surface [19]:

$$114 \quad (P + SM)\cos\alpha + R = I \quad (1)$$

115 where, P indicates precipitation (mm/h); SM indicates snowmelt water (mm/h); I indicates
 116 infiltration (mm/h); R indicates runoff (mm/h) and α is the slope angle ($^{\circ}$).

117 Snow accumulation models often use average air temperature to distinguish the precipitation as
 118 rainfall or snowfall [20, 21]. The threshold value of air temperature to differentiate rainfall and
 119 snowfall is 0°C and snowmelt is assumed to occur when snowpack is present on the ground with

120 the positive air temperature.

121 The snowfall is equal to the precipitation under negative air temperature [19].

$$122 \quad SF = P \times f_s \times SCF \quad (2)$$

123 where, SF is snowfall (mm/h); f_s is snow fraction, and SCF is snow correction factor with the value
124 of 1 [22]. The snow fraction, f_s is defined as,

$$125 \quad f_s = 0 \text{ (if } T_a > T_f \text{) and } f_s = 1 \text{ (if } T_a \leq T_f \text{)} \quad (3)$$

126 where, T_a is average air temperature (°C) and T_f is freezing point temperature (0 °C).

127 When air temperature is negative, snow will accumulate on the surface of the soil. Once the air
128 temperature is positive, the snow will melt into water then penetrate into soil. The amount of melted
129 water is calculated in the form of the snow water equivalent.

$$130 \quad \Delta SWE = SF - SM \quad (4)$$

131 where, ΔSWE is difference in snow water equivalent (mm/h).

132 Governing equations for non-isothermal seepage flow

133 The 2D seepage flow is governed by the equation given by Richards [23] and Kim and Heydinger
134 [24].

$$135 \quad \frac{\partial}{\partial x} \left(k_x(\psi) \frac{\partial \psi}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y(\psi) \left(\frac{\partial \psi}{\partial y} + 1 \right) \right) = c(\psi) \frac{\partial \psi}{\partial t} \quad (5)$$

136 where, $k_x(\psi)$ and $k_y(\psi)$ indicate unsaturated hydraulic conductivities in x-direction and y-direction
137 (m/s), respectively; ψ indicates pore water pressure head (m); $c(\psi)$ indicates specific moisture
138 capacity (1/m).

139 The 2D thermal flow is governed by the equation given by Kim and Heydinger [24].

$$140 \quad \frac{\partial}{\partial x} \left(\lambda_T \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda_T \frac{\partial T}{\partial y} \right) - v_x C_w \frac{\partial (T)}{\partial x} - v_y C_w \frac{\partial (T)}{\partial y} = C \frac{\partial T}{\partial t} \quad (6)$$

141 where, T is temperature (°C); λ_T is thermal conductivity (kJ/(Day·m·°C)); v_x and v_y are the velocities
142 of the water flow in x and y directions (m/s); C_w is the heat capacity of water (kJ/(m³·°C)); C is the

143 volumetric heat capacity ($\text{kJ}/(\text{m}^3 \cdot ^\circ\text{C})$).

144 **Meteorological monitoring data analysis and future climate prediction**

145 Meteorological monitoring data analysis

146 To semi-quantitatively assess the influences of climate changes on the uncertainty of climate factors
147 in different scales (e.g. world, country (Japan), and city (Sapporo, a city located in the seasonally
148 cold region of northern Japan)), this study analyzes the trend of the annual average air temperature
149 deviation (Fig. 2(a)), annual cumulative precipitation deviation (Fig. 2(b)), magnification of
150 precipitation (Fig. 2(c)), and the number of days with air temperature below zero (Fig. 2(d)) by the
151 regression analysis of the meteorological monitoring data of the past 120 years (1900-2020) of the
152 world, Japan, and Sapporo referred from JMA. The benchmark of deviation is the average value of
153 30 years (1981-2010). The annually average air temperature deviation shown in Fig. 2(a) and
154 annually cumulative precipitation deviation shown in Fig. 2(b) are the difference between them of
155 each year and this benchmark. Fig. 2(a) shows that the world annually average air temperature
156 increases approximately $0.8\text{ }^\circ\text{C}$ per 100 years, while the values of Japan and Sapporo are $1.27\text{ }^\circ\text{C}$
157 per 100 years and $2.46\text{ }^\circ\text{C}$ per 100 years, respectively. It means that global warming has a significant
158 impact on Japan, especially on high latitude area or seasonal snowy cold regions in Japan like
159 Sapporo.

160 Fig. 2(b) plots the annually cumulative precipitation deviation. Six intervals of 20 years are
161 divided over the past 120 years to analyze the change of the annual cumulative precipitation
162 deviation. It can be seen that the number of positive values on the three scales are 12, 14, and 15,
163 respectively, in the past 20 years (2000-2020), which are all the maximum values since 1920. It
164 means from 1920, the number of years with heavy rainfall is increasing. Fig. 2(c) and Fig. 2(d)
165 shows the magnification of precipitation (the ratio of annually cumulative precipitation of each year

166 to the benchmark) and the number of days with air temperature below zero in Sapporo, respectively.

167 The results of fitting curves display that the magnification of precipitation increases by 0.094 per

168 100 years, and the number of days with air temperature below zero decreases 16.8 days per 100

169 years in Sapporo. It means that the precipitation is increasing and winter is getting shorter in

170 Sapporo.

173 **Fig. 2.** Meteorological monitoring data of the world, Japan, and Sapporo referred from JMA. (a).

174 annually average air temperature deviation; (b) annually cumulative precipitation deviation; (c)

175 magnification of precipitation, and (d) number of days with air temperature below zero.

176 To investigate whether climate change has different effects on air temperature in different seasons,

177 the air temperature change in four seasons, i.e., December-January-February (DJF),

178 March-April-May (MAM), June-July-August (JJA), and September-October-November (SON), in

179 the world, Japan, and Sapporo are analyzed separately as shown in Fig. 3. It is recognized that in all
 180 seasons, the influences of climate change on the air temperature of Sapporo are very significant,
 181 followed by Japan, compared with the world. It is noted that in Sapporo, climate change has the
 182 most obvious effect on the air temperature in the Winter season (DJF, increases by 2.89 °C per 100
 183 years), followed by Spring season (MAM, increases by 2.63 °C per 100 years), and then Autumn
 184 season (SON, increases by 2.30 °C per 100 years), and finally Summer season (JJA, increases by
 185 2.03 °C per 100 years). The increase in average air temperature in Autumn season and Winter
 186 season will cause the thickness of frozen soil to decrease, and in Spring season will cause the
 187 increase of snowmelt water, which can be considered as the main reason of the increase in the
 188 geological disasters in the cold regions in Japan.

Fig. 3. Temperature of the world, Japan, and Sapporo change in different seasons, (a) DJF; (b)

MAM; (c) JJA, and (d) SON.

Future climate prediction based on dynamical downscaling techniques

To further analyze the future climate change, the future climate data (2090-2091), i.e., meteorological simulation data at Nakayama Pass, Sapporo, Hokkaido, Japan is estimated by using another dynamical downscaling technique, the hybrid-downscaling method proposed by Yamada et al. [25]. The meteorological simulation data is obtained by downscaling the outputs of 3 different RAMs with lateral boundary conditions from 3 different GCMs. Fig. 4 shows past meteorological monitoring data (2012-2013) and future meteorological simulation data (2090-2091) at Nakayama Pass. It shows that the average maximum air temperature increases 0.6 °C, and the average minimum air temperature increases by 3.29 °C in 2090-2091. Therefore, the average air temperature increases by about 1.945 °C in the next 80 years at Nakayama Pass, which is consistent with an increase of 2.46 °C per 100 years in Sapporo obtained from the regression analysis results of the meteorological monitoring data (Fig. 2(a)). Besides, the annual cumulative precipitation increases from 1882 mm (2012-2013) to 2131 mm (2090-2091). The magnitude of the precipitation increases by about 0.13, which is slightly larger than the value of the meteorological analysis data (0.094 per 100 years) in Sapporo shown in Fig. 2(c).

Fig. 4. Climate in the past and future at Nakayama Pass: (a) max. air temperature; (b) min. air temperature; (c) precipitation during 2012-2013; (d) precipitation during 2090-2091; (e) wind speed.

Instability assessment of homogeneous conceptual slope under climate change

According to meteorological analysis data obtained from the regression analysis and the meteorological simulation data obtained from hybrid-downscaling method, climate change is gradually increasing the precipitation and air temperature in Japan (especially in cold regions). To assess the influences of climate change on the occurrence of slope failure and its probability distribution, water content simulation and slope stability analysis were performed using a 2D

219 homogeneous conceptual slope model with the consideration of freeze-thaw actions using the slope
 220 stability assessment approach. The applicability and reliability of the slope stability assessment
 221 approach in the analysis of slope stability during the snow-melting season and heavy rainfall season
 222 in cold regions has been clearly validated by Siva Subramanian et al. [18].

223 Numerical model and boundary conditions

224 A 2D numerical model is established to simulate slope stability under climate change. Fig. 5 shows
 225 the numerical model used in this study and the applied boundary conditions. The numerical models
 226 are simulated with different slope heights (5 m, 10 m, 15 m, and 20 m) and different slope angles
 227 (30° , 35° , 40° , and 45°) to reflect various in situ conditions of homogeneous conceptual slopes.
 228 During the simulation, climate data is applied on the soil surface (ab, bc, cd in Fig. 5). Adiabatic
 229 boundary conditions are set at the right side (de in Fig. 5), the bottom side (ef in Fig. 5), and the left
 230 side (af in Fig. 5). Due to the left side of the model is assumed to adjacent to the bedrock, no flow
 231 boundary is applied on the left side (af in Fig. 5) and free drainage boundary is applied on the right
 232 side (de in Fig. 5) and bottom side (ef in Fig. 5).

233
 234 **Fig. 5.** 2D numerical homogeneous slope model with applied boundary conditions.

235 Fig. 6 shows the original climate data at Nakayama Pass during 2012-2013, which were obtained
 236 from the AMeDAS. According to the regression analysis results of the historical meteorological

237 monitoring data of Sapporo, the assumption for precipitation is 1.2 times increased and for air
 238 temperature is 2 °C increased in the 80 years later. Therefore, 4 kinds of assumed climate boundary
 239 conditions as listed in Table 1 are applied to 16 kinds of numerical models (4 slope heights $\times$ 4
 240 slope angles). A total of 64 numerical simulations are conducted for Nakayama Pass. Table 2 lists
 241 the soil material properties. Dry density (ρ_d), porosity (n), effective cohesion (c'), effective internal
 242 friction angle (ϕ'), and saturated hydraulic conductivity (k_s), were measured by Hokkaido Regional
 243 Development Bureau [26]. The soil water characteristic curve (SWCC) of the slope is estimated
 244 from the grain size distribution curve by referring to Fredlund et al. [27]. The rest parameters are
 245 estimated based on the grain size curve of soil [28].

246
 247 **Fig. 6.** Original climate data obtained from the AMeDAS at Nakayama Pass.

248 **Table 1.** Study cases under various weather conditions.

Case name	Precipitation condition	Temperature condition
Case 1	Original Precip. (AMeDAS)	Original Temp. (AMeDAS)
Case 2	Original Precip. (AMeDAS)	Original Temp.+ 2°C
Case 3	Original Precip. $\times$ 1.2	Original Temp. (AMeDAS)

Case 4	Original Precip. $\times 1.2$	Original Temp. $+ 2^{\circ}\text{C}$
--------	-------------------------------	--------------------------------------

Table 2. Soil properties used for the simulation.

Soil properties	Value
Dry density of soil (ρ_d)	1400 kg/m ³
Porosity (n)	0.47
Unfrozen thermal conductivity (λ_u)	127.04 kJ/(Day·m·°C)
Frozen thermal conductivity (λ_f)	132.24 kJ/(Day·m·°C)
Volumetric water content of soil at 0°C (θ_{wf})	0.15 m ³ /m ³
Hydraulic conductivity of saturated soil (k_s)	5.62×10^{-7} m/s
Unfrozen volumetric heat capacity (ζ_u)	2237 kJ/(m ³ ·°C)
Frozen volumetric heat capacity (ζ_f)	1624 kJ/(m ³ ·°C)
Effective cohesion (c')	9.75 kPa
Effective angle of internal friction (ϕ')	35°

Simulation results and discussions

The calculated snow depth, daily snowmelt, daily infiltration, and daily rainfall under the four climate conditions are shown in Fig. 7. Fig. 7(a) displays the calculated and measured snow depth. Seeing Fig. 7(a), the results suggest that the calculated snow depth under case 1 is consistent with the measurement data, meaning that the simulation results are reliable. It is recognized that when the air temperature is increased by 2 °C, the time when the snow disappears is advanced from June 1st (case 1) to May 23rd (case 2), and the maximum snow depth is decreased from 2.79 m (case 1) to 2.66 m (case 2). When the precipitation is increased by 1.2 times, the maximum snow depth is increased from 2.79 m (case 1) to 3.42 m (case 3). Fig. 7(b) and Fig. 7(c) show that the increase in the air temperature increases snowmelt and infiltration during the Spring season and the end of the

260 Autumn season. The main reason is that on one hand air temperature controls snowmelt during
 261 those periods and the snowmelt water is the main water supply of the infiltration. On the other hand,
 262 when the average air temperature is increased by 2 °C, during Spring season and Autumn season,
 263 some negative air temperatures become positive, which causes some snowfalls are converted into
 264 the rainfalls as shown in Fig. 7(d). At the same time, more snow on the ground surface melt into
 265 water and infiltrate into the soil reducing the slope stability.

268 **Fig. 7.** Simulation results vs. time (a) snow depth, (b) daily snowmelt, (c) daily infiltration, and (d)
 269 daily rainfall.

270 To assess the influences of climate change on slope stability subjected to snowmelt and heavy
 271 rainfall respectively, a year is divided into two different intervals according to the different causes
 272 of slope failures: Winter-Spring period (the key factor of slope failure is snowmelt water) and

273 Summer-Autumn period (the key factor of slope failure is heavy rainfall). The probability
274 distribution is described by probability density function, which is a function that can be used to
275 describe the probability of the slope failures in a time interval (one month in this study).

$$276 \quad f(x) = \frac{1}{\sqrt{\pi/2} \times \sigma} \exp\left(-2 \times \frac{(x-\mu)^2}{\sigma^2}\right) \quad (7)$$

277 where, $f(x)$ is the normal density at x , which is parametrized in terms of the mean and the variance,
278 denoted by σ and μ^2 , respectively.

279 Fig. 8 (a) and Fig. 8 (b) show the total number of days with slope failure (FOS<1) and the fitting
280 normal density curve (NDC) of numerical results during the Winter-Spring period and the
281 Summer-Autumn period, respectively. Fig. 8 suggests that when air temperature increases 2 °C
282 (case 2) compared with the original climate conditions (case 1), during the Winter-Spring period,
283 the μ will decrease and the σ will increase. The NDC becomes chunky and moves to March. It
284 means that the increased air temperature causes more slope failures to occur earlier and broadens
285 the time domain of slope failures in the Spring season. The main reason is that the increased air
286 temperature leads to the shortening of Winter season and the advancement of the snow-melting
287 season.

288 As shown in Fig. 7, the melting of snow is advanced, which causes the slope failures occur earlier.
289 More slope failures occur in March and fewer slope failures occur in April broadening the time
290 domain of slope failures in the Spring season. During the Summer-Autumn period, it is the exact
291 opposite that the increased air temperature increases the value of μ and decreases the value of σ . The
292 NDC becomes thin and tall, and moves to September. It means that the increased air temperature
293 causes more slope failures to occur later and narrows the time domain of slope failures in the
294 Autumn season. When precipitation increases 1.2 times (case 3) compared with the original climate
295 conditions (case 1), during the Winter-Spring period, the μ will increase and the σ will decrease, and

296 during the Summer-Autumn period, μ will decrease and the σ will increase. It means that the
 297 increased precipitation causes more slope failures to occur later and narrows the time domain of
 298 slope failures in the Spring season, and more slope failures to occur earlier and broadens the time
 299 domain of slope failures in the Summer season.

300 When considering changes in air temperature and precipitation together, it can be seen that during
 301 the Winter-Spring period both μ and σ decrease, while during the Summer-Autumn period both μ
 302 and σ increase. This is consistent with the trend of slope failures in Japan investigated by the MLIT
 303 from 2008 to 2017 as shown in Fig. 9. It indicates that during the Winter-Spring period the
 304 occurrence of slope failures will be more concentrated in April, while during the Summer-Autumn
 305 period, the time domain of its occurrence will become wider. Therefore, the numerical results are
 306 believable through the verification of the investigation results. It indicates that the meteorological
 307 analysis data are reliable and the proposed assessment approach is available for evaluating the
 308 effects of climate changes on slope instability.

310 **Fig. 8.** Total number of days with slope failure and the fitting normal density curve (NDC) of 64
 311 numerical models. (a) during the Winter-Spring period; and (b) during the Summer-Autumn period.

Fig. 9. Annual average number of geo-disasters in each month and the fitting normal density curve (NDC) of investigation results. (a) during 2008-2012; and (b) during 2013-2017.

Assessment of actual highway slope instability under climate change

In previous chapter, an assessment approach for evaluating the effects of climate changes on slope instability is proposed using the 2D homogeneous conceptual slope model with considering different slope heights and different slope angles. To check the effectiveness of the above assessment approach, assessment of instability of an actual highway embankment slope with the local layer geometry is done by applying the past (meteorological monitoring data during 2012-2013) and predicted future climate data by dynamical downscaling techniques (meteorological simulation data during 2090-2091). Along the national highway route 230 in Hokkaido, Japan, at Nakayama Pass, the slope failure occurred successively on May 4th, 2012, and April 7th, 2013 as shown in Fig. 10. On May 4th, 2012, within the range of about 40 m in length and up to 110 m in transverse width, approximately 13,000 m³ of soil collapsed and caused 20 days road closure. On April 7th, 2013, another slope failure occurred with more than 11,000 m³ of sediment collapsed [29]. The increase in the snowmelt water due to climate change was considered as the main causes of the slope failures.

Fig. 10. Slope failures at Nakayama Pass on Route 230.

Numerical model of the highway slope at Nakayama Pass

The parametric analysis of slope failures at Nakayama Pass is performed by inputting meteorological monitoring data during 2012-2013 (measured by AMeDAS) and meteorological simulation data during 2090-2091 (simulated by GCMs) as shown in Fig. 4. The 2D numerical model with the slope stratigraphy for highway slope at Nakayama Pass is established, which consists of three layers of embankment filling, talus, and bedrock. The measured groundwater table is given in Fig. 11. Table 3 lists the five kinds of boundary conditions for parametric studies. The soil properties are given in Table 4. The bedrock is modeled as an impenetrable material.

Fig. 11. 2D numerical highway slope model at Nakayama Pass.

Table 3. Study cases under various weather conditions for parametric studies.

Boundary name	Air temp. (2012/2013)	Precip. (2012/2013)	Wind speed (2012/2013)	Air temp. (2090/2091)	Precip. (2090/2091)	Wind speed (2090/2091)
B1	O	O	O	×	×	×
B2	×	O	O	O	×	×
B3	O	×	O	×	O	×
B4	O	O	×	×	×	O
B5	×	×	×	O	O	O

× – unapplied weather data; o – applied weather data.

Table 4. Soil properties of the actual highway slope at Nakayama Pass.

Soil properties	Embankment filling	Talus materials
Dry density of soil (ρ_d)	1400 kg/m ³	1200 kg/m ³
Porosity (n)	0.47	0.53

Unfrozen thermal conductivity (λ_u)	127.04 kJ/(Day·m·°C)	103.7 kJ/(Day·m·°C)
Frozen thermal conductivity (λ_f)	132.24 kJ/(Day·m·°C)	135.7 kJ/(Day·m·°C)
Volumetric water content of soil at 0°C (θ_{wf})	0.15 m ³ /m ³	0.10 m ³ /m ³
Hydraulic conductivity of saturated soil (k_s)	5.62×10^{-7} m/s	1×10^{-4} m/s
Unfrozen volumetric heat capacity (ζ_u)	2237 kJ/(m ³ ·°C)	2398 kJ/(m ³ ·°C)
Frozen volumetric heat capacity (ζ_f)	1624 kJ/(m ³ ·°C)	1392 kJ/(m ³ ·°C)
Effective cohesion (c')	9.75 kPa	52 kPa
Effective angle of internal friction (ϕ')	35°	11.36°

344 Simulation results and discussions

345 To determine the main climate factors affecting the slope stability in the future, the variation in the
346 FOS, ground surface temperature, volumetric (vol.) water content and infiltration are given in Fig.
347 12. Fig. 12(a) displays that during snow-melting season, the FOS has a rapidly decrease due to the
348 snowmelt water infiltration increases the vol. water content as shown in Fig. 12(d), which causes
349 the slope to be in an unstable state (FOS<1). After the snow-melting season, the FOS gradually rises
350 to the normal level. It is noted that there is a much longer (more than doubled) unstable state of the
351 highway slope at Nakayama Pass under B3 (53 days) and B5 (64 days) boundary conditions
352 compared with the B1 (22 days) boundary condition. However, the unstable state of the highway
353 slope at Nakayama Pass has almost no significant increase under B2 (23 days) and B4 (25 days)
354 boundary conditions. It means that climate change (especially the increase in precipitation) in the
355 future will enhance the instability of the slopes and lead to more slope failures occur.

356 Fig. 12(b) displays that the cumulative infiltration between March 1st and July 1st (surrounded by
357 the red dash box) is 1142.1mm, 1283.7 mm, and 1173.3 mm under B1, B2, and B4 boundary
358 condition, respectively. The difference in infiltration is almost negligible. However, the cumulative

359 infiltration between March 1st and July 1st is 1930.4 mm and 2055.2 mm under B3 and B5 boundary
 360 conditions with an increase of approximately 69% and 80%, respectively. During this period, the
 361 ground surface is unfrozen as shown in Fig. 12(c). Therefore, the infiltration increases the vol.
 362 water content eventually causes slope failure (see Fig. 12(d)). Accordingly, it can be obtained that
 363 climate change (especially the increase in precipitation) in the future will increase the infiltration
 364 and cause more slope failures during the Spring season.

367 **Fig. 12.** Simulation results of (a) FOS vs. time, (b) Daily infiltration vs. time, (c) Ground surface
 368 temperature vs. time, and (d) Vol. water content vs. time (the red dash line is saturated vol. water
 369 content).

370 Conclusions

371 The main findings derived from this study are summarized as follows:

372 1. According to the regression analysis results of the meteorological monitoring data during the past
373 120 years, affected by global warming (average air temperature in the world increases
374 approximately 0.8 °C per 100 years), the air temperature rise in some cold cities is more serious
375 (such as in Sapporo, Japan, average air temperature increases 2.46 °C per 100 years). Meanwhile,
376 the precipitation is also increasing and Winter is getting shorter in these cold regions.

377 2. Climate change has the more obvious influences on the increase in the air temperature in the
378 Winter season (DJF) and Spring season (MAM) compared with the Autumn season (SON) and
379 Summer season (JJA). During the Spring season (MAM) and the end of the Autumn season (SON),
380 the increase in the air temperature causes the increase in the snowmelt and infiltration.

381 3. The increased air temperature leads to the shortening of winter season and the advancement of
382 the snow-melting season. It causes the slope failures occur earlier and broadens the time domain of
383 slope failures in the Spring season, and causes more slope failures to occur later and narrows the
384 time domain of slope failures in the Autumn season. The increased precipitation causes more slope
385 failures to occur later and narrows the time domain of slope failures in the Spring season, and
386 causes more slope failures to occur earlier and broadens the time domain of slope failures in the
387 Summer season. When considering changes in precipitation and air temperature together, during the
388 Winter-Spring period, the occurrence of slope failures will be more concentrated in April, while
389 during the Summer-Autumn period, the time domain of its occurrence will become wider.

390 4. Climate change (especially the increase in precipitation) in the future will increase the infiltration
391 during the Spring season. It will lengthen the time that the highway slope is in an unstable state,
392 thereby enhancing the instability of the slopes and lead to more slope failures occur in the future.

393 The research findings propose an effective method to semi-quantitatively evaluate the influences of
394 climate change on slope stability and the probability distribution of the slope failures by using

numerical simulation, regression analysis, and statistical analysis. It can be used in the adjustment of counter measures of geo-disaster at the actual design and maintenance works in the future. In addition, taking effects of climate change on the geo-disaster into the early warning system will be the future assignment of this study.

Abbreviations

RAMs: Regional Atmospheric Models; GCMs: General Circulation Models; NDC: Normal Density Curve; 2D: 2-dimensional; FEM: Finite Element Model; JMA: Japan Meteorological Agency; MLIT: Ministry of Land, Infrastructure, Transport, and Tourism; AMeDAS: Automatic Meteorological Data Acquisition System; FOS: Factor of Safety; LEM: Limit Equilibrium Method; DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; SON: September-October-November; SWCC: Soil Water Characteristic Curve.

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Authors' contributions

YZ drafted this manuscript, analyzed climate data and performed the thermal and mechanical numerical simulations. TI guided the works of this study and the writing of this manuscript, and interpreted the climate data. TJY conducted the general circulation modeling and future climate prediction. SSS conducted the thermal and mechanical modelling and collected the past climate data. The author(s) read and approved the final manuscript.

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418 **Availability of data and materials**

419 The datasets used and/or analyzed during the current study are available from the corresponding
420 author on reasonable request.

421 **Declarations**

422 **Competing interests**

423 The authors declare that they have no competing interests.

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505

Figures

Figure 1

Slope stability assessment approach (adapted from [18]).

Figure 2

Meteorological monitoring data of the world, Japan, and Sapporo referred from JMA. (a). annually average air temperature deviation; (b) annually cumulative precipitation deviation; (c) magnification of precipitation, and (d) number of days with air temperature below zero.

Figure 3

Temperature of the world, Japan, and Sapporo change in different seasons, (a) DJF; (b) MAM; (c) JJA, and (d) SON.

Figure 4

Temperature of the world, Japan, and Sapporo change in different seasons, (a) DJF; (b) MAM; (c) JJA, and (d) SON.

Figure 5

2D numerical homogeneous slope model with applied boundary conditions.

Figure 6

Original climate data obtained from the AMeDAS at Nakayama Pass.

Figure 7

Simulation results vs. time (a) snow depth, (b) daily snowmelt, (c) daily infiltration, and (d) daily rainfall.

Figure 8

Total number of days with slope failure and the fitting normal density curve (NDC) of 64 numerical models. (a) during the Winter-Spring period; and (b) during the Summer-Autumn period.

Figure 9

Annual average number of geo-disasters in each month and the fitting normal density curve (NDC) of investigation results. (a) during 2008-2012; and (b) during 2013-2017.

Figure 10

Slope failures at Nakayama Pass on Route 230.

Figure 11

2D numerical highway slope model at Nakayama Pass.

Figure 12

Simulation results of (a) FOS vs. time, (b) Daily infiltration vs. time, (c) Ground surface temperature vs. time, and (d) Vol. water content vs. time (the red dash line is saturated vol. water content).