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SEISMIC RISK OF ISOLATED HIGHWAY BRIDGES WITH HIGH DAMPING RUBBER BEARINGS IN COLD REGIONS

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Abstract. The impact of low temperatures on the seismic performance of isolated bridges with high damping rubber (HDR) bearings cannot be ignored. In cold regions, the effectiveness of the isolation system is highly likely to be weakened, leading to a higher seismic risk for bridges. However, a lack of reasonable seismic risk assessment exists for isolated bridges in low-temperature environments. This paper aims to assess the seismic risk of isolated highway bridges with HDR bearings in cold regions. A prototype of the bridge is selected, and the incremental dynamic analysis (IDA) is conducted for seismic performance evaluation. The fragility surface incorporating intensity and temperature measures is evaluated. The seismic damage probability is estimated. It can be found that the probability of a bridge with no damage, in this case, decreases from 0.681 to 0.598 by 8.3% when considering the temperature effect, while the probability of all damage states increases accordingly. The proposed method will provide a reference for seismic risk assessment of isolation bridges in cold regions. The optimal strategies can be offered for the maintenance and management of existing structures as well as the design of new structures.

1 INTRODUCTION

Seismic isolation has been widely recognized as an effective strategy for enhancing the seismic resilience of the bridge by extending its natural period and reducing seismic forces transmitted to the superstructure. High damping rubber (HDR) bearing, as one of the efficient isolation devices, provides superior energy dissipation capacity and has been extensively implemented in engineering practice. However, the mechanical properties of HDR material are highly sensitive to temperature variations, particularly in a low-temperature environment. Experimental investigations proved that the initial stiffness of the rubber bearing increased at low temperatures, showing a significant property of temperature dependence. Another noteworthy aspect is the heating effect of the bearings. The inner temperature of bearings increases due to energy dissipation when bearings are subjected to external loads [1]. The rising temperature will lead to a continuous reduction in stiffness, which makes the hysteretic behavior of bearings more complex [2]. To better present the hysteretic behavior of HDR bearings, researchers have proposed a series of numerical models based on the classic models, including the bilinear elasto-plastic model [3], Park-Wen model [4] (Bouc-Wen model [5, 6]), Ozdemir model [7], etc. Specifically, A thermo-coupled restoring force model [8, 9] was proposed to consider the heating effect with expected accuracy. A multi-layer thermo-mechanical modified Bouc-Wen (MTBW) model [10, 11] was then developed to illustrate the thermal conduction within HDR bearings.

The purpose of proposing the temperature-dependent model is to accurately represent the mechanical behavior of bearings at low temperatures and enhance the accuracy of seismic performance for structures. Researchers [12-14] have already utilized these models of isolated bearing to evaluate the seismic performance of isolated bridges under low-temperature environments. As concerns, the effectiveness of the isolation system was weakened at low ambient temperatures, with the reduction of maximum shear strain and energy dissipation of the bearing as well as the increase of displacement of the bridge pier [15]. However, most studies have primarily focused on lead rubber (LR) bearings, with little attention given to HDR bearings.

In addition, seismic risk assessment, as a process to evaluate the potential impact of seismic events on structures, including buildings, bridges, tunnels [16-18], etc., has grown in importance in recent years due to the increased awareness of earthquake risks and the need for resilient infrastructure. The key components of seismic risk assessment of structures involve hazard analysis, fragility analysis, and seismic damage probability estimation. To evaluate the effect of temperature variations on structures, temperature was incorporated into the fragility analysis as a variable considered simultaneously with the intensity measure. Furthermore, the temperature exceedance probability obtained from the temperature distribution was used in the structural seismic damage probability estimation. However, seismic risk assessment considering temperature variations is currently limited to building structures.

To fill the research gap, this paper proposes a framework of seismic risk assessment for isolated highway bridges with HDR bearings, considering temperature variations. This framework can comprehensively assess the seismic damage probability in low-temperature regions. The main contributions of this work are summarized as follows.

- The temperature measure is introduced into the framework of seismic risk assessment to evaluate the non-ignorable temperature effect on the seismic performance of temperature-sensitive components.
- The fragility surfaces of components, incorporating varying seismic intensities and ambient temperatures, are provided to evaluate the vulnerability of components and structure with the temperature effect.
- The seismic damage probability of the structure based on the fragility surface is estimated to consider the temperature effect.

The rest of this paper is organized as follows. Section 2 introduces the framework of seismic risk assessment, considering the temperature effect. Section 3 presents the prototype and numerical model of an isolated highway bridge with HDR bearings. Section 4 demonstrates the detailed seismic risk assessment of the isolated bridge and corresponding discussions. Section 5 gives the remarkable conclusions of this study.

2 FRAMEWORK OF SEISMIC RISK ASSESSMENT IN COLD REGIONS

In this section, a framework of seismic risk assessment considering temperature variations will be illustrated, including the dynamic and fragility analyses, seismic hazard and temperature distribution analyses, and seismic damage probability estimation. Different from the conventional seismic risk assessment, the effect of ambient temperature on structures will be incorporated in the analysis for cold regions.

2.1 Dynamic and fragility analyses

Incremental dynamic analysis (IDA) is conducted to evaluate the seismic performance of the isolated bridge with an HDR bearing. By analyzing an ensemble of IDA curves obtained from multiple ground motion inputs, fragility curves can be calculated, allowing for the evaluation of structural response characteristics and damage mechanisms while considering the uncertainty of ground motions.

The specific amplitude scaling factor λ_i can be calculated by

$$\lambda_i = \frac{\Delta IM \times i}{\max IM} \tag{1}$$

where ΔIM is the increment of intensity measure (IM); $\max IM$ is the maximum intensity measure determined in the time history analysis. The peak ground velocity (PGV) is selected as the IM in this case.

Since the hysteretic behavior of the HDR bearing is significantly affected by the ambient temperature, similarly, the temperature measure (TM) is introduced. The seismic performance of the isolated bridges will be evaluated under different TMs within the scope of interest through the time history analysis. The fragility function based on the IDA can be fitted with a log-normal cumulative distribution function (CDF) and expressed as

$$P(DS \geq ds_i | IM, TM) = \Phi\left[\frac{\text{In}(im) - \lambda_{IM}}{\xi_{IM}}\right] \tag{2}$$

where DS is the damage state; $\Phi(\cdot)$ is the standard normal CDF; λ_{IM} and ξ_{IM} are the mean and standard deviation of IM reaching the specified ds_i based on the lognormal distribution.

2.2 Seismic hazard and temperature distribution analyses

Seismic hazard refers to the potential ground motion that occurs at a specific location due to an earthquake. The hazard curve is obtained through historical earthquake data and seismic hazard analysis, typically requiring curve fitting. In this framework, the seismic hazard curve can be estimated by the exponential function, as

$$\lambda_{IM}(im) = P(IM > im) = a \cdot \exp(b \cdot im) \tag{3}$$

where a and b are parameters of the exponential function.

The mean annual exceedance probability of temperature also needs to be estimated for temperature consideration. To facilitate probability analysis, assume that the temperature distribution follows a normal distribution. The annual exceedance probability of temperature can be expressed as

$$\lambda_{TM}(tm) = P(TM > tm) = 1 - \Phi\left(\frac{tm - \mu_{TM}}{\sigma_{TM}}\right) \tag{4}$$

where μ_{TM} and σ_{TM} are the mean and standard deviation of the temperature distribution of TM.

2.3 Seismic damage probability estimation considering temperature

Seismic damage probability can be defined as the joint probability distribution of a component or structure reaching a specific DS, considering the occurrence probability of the seismic hazard. When the effect of environmental temperature on the response of the structure is non-ignorable, the temperature exceedance probability should be considered in probabilistic analysis, similar to the occurrence probability of seismic hazard. The conditional probability of a component or structure reaching ds_i under the given im_k and tm_j can be obtained from **Eq. (2)**, expressed as

$$P(ds_i|IM = im, TM = tm) = \begin{cases} 1 - P(DS \geq ds_{i+1}|im, tm) & i = 0 \\ P(DS \geq ds_i|im, tm) - P(DS \geq ds_{i+1}|im, tm) & 1 \leq i < n_{ds} \\ P(DS \geq ds_i|im, tm) & i = n_{ds} \end{cases} \tag{5}$$

where n_{ds} is the total number of DSs.

The probability of a component or structure being in a certain damage state ds_i can be calculated by combining damage probability as well as the probability of seismic hazard and temperature distribution in integral, as

$$P(ds_i) = \iint_{\Lambda_{\mathrm{IM}},\Lambda_{\mathrm{TM}}} P(ds_i|im, tm)\, d\lambda_{IM}(im)\, d\lambda_{TM}(tm) \tag{6}$$

where Λ_{IM} and Λ_{TM} are domains of $\lambda_{IM}(im)$ and $\lambda_{TM}(tm)$. In practice, **Eq. (6)** can be approximated by summing over discrete values of IMs and TMs, which can be expressed as

$$P(ds_i) \approx \sum_{j=1}^{n_{tm}} \sum_{k=1}^{n_{im}} P\left(ds_i|im_k, tm_j\right) \Delta\lambda_k \Delta\lambda_j \tag{7}$$

where n_{im} and n_{tm} are numbers of discrete intervals for IM and TM, respectively; $\Delta\lambda_k$ and $\Delta\lambda_j$ are probabilities of im_k and tm_j.

3 DESCRIPTION OF ISOLATED BRIDGE MODEL

A highway isolated bridge equipped with HDR bearings is selected for dynamic analysis, based on the Materials for the Seismic Design of Road Bridges [19] in Japan. The bridge is designed in accordance with the Specifications for Highway Bridges, Part V: Seismic Design [20]. It is categorized as a Class B bridge, indicating a structure of particular high importance in seismic design. The isolated bridge features a seven-span continuous steel girder, with each span measuring 40 m. The superstructure is supported by five HDR bearings, positioned at the base of each pier and abutment. The substructure comprises six piers and two abutments, with heights of 12.0 m and 9.5 m, respectively.

A nonlinear MDOF model of an isolated bridge is developed to assess its seismic performance at low temperatures. **Figure 1a** presents the numerical model of a typical RC bridge pier, comprising superstructure, isolation bearing, pier, and foundation. The design parameters of the bridge pier are summarized in **Table 1**. The superstructure is modeled as a mass point (Node 1), while the isolation bearing is represented by a nonlinear spring (Node 2). **Figure 1b** illustrates the composition of the HDR bearing and its corresponding restoring force model. The MTBW model [10, 11] is employed instead of the bilinear model used in the seismic design code, due to its capability to accurately capture the hysteretic behavior of HDR bearings under varying ambient temperatures. The design parameters of the HDR bearings are provided in **Table 2**. The bridge pier is represented by mass points (Nodes 3 and 4) and a rigid element. An elasto-plastic rational spring (Node 5) is introduced at the pier base to simulate yielding behavior, with its nonlinear characteristics modeled using the Clough model [21] to capture stiffness degradation in the RC pier, as shown in **Figure 1c**. The ratio of first stiffness and second stiffness is set as 0.05. The temperature effect on the behavior of the pier is not considered in this model. The spread foundation is incorporated as Node 6, with soil-foundation interaction modeled through a horizontal spring and a rotational spring at Node 7. The fundamental natural period of the structure is 1.67 seconds.

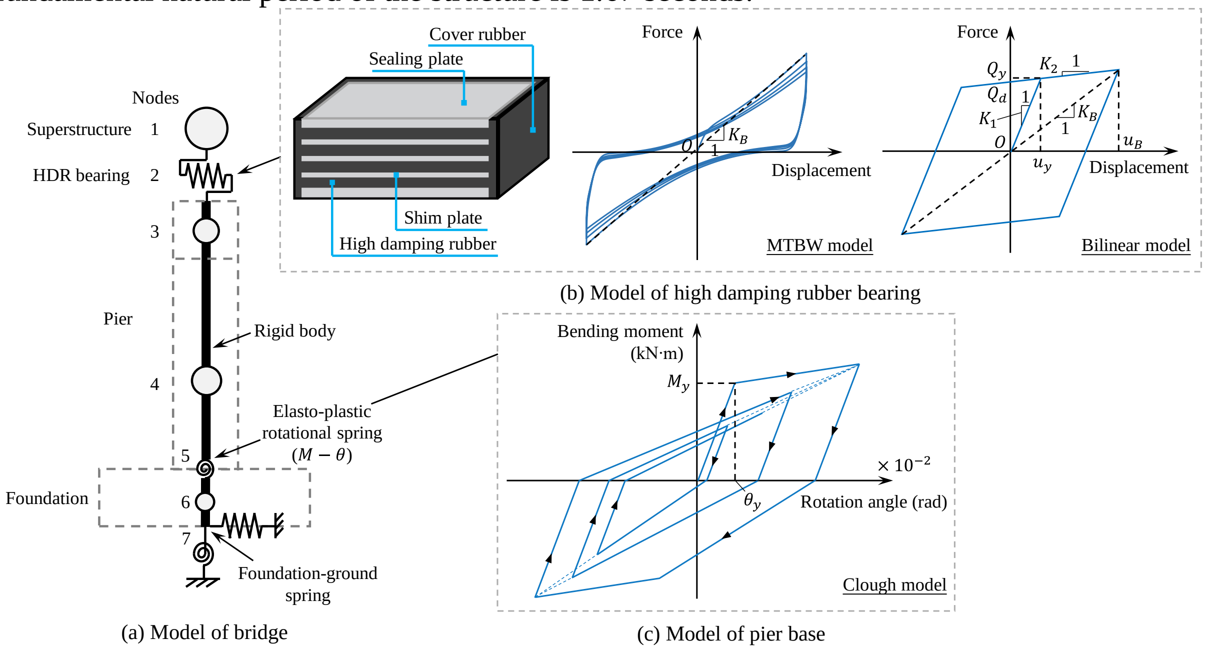


Figure 1: Numerical model of bridge with HDR bearing and pier

Table 1: Design parameters of bridge pier [19]

Node	Height (m)	Mass		Pier base rotational spring	
		Horizontal (ton)	Rotational (ton·m)	Yielding bending moment (kN·m)	2.11×10^4
				Yielding rotation angle (rad)	0.279×10^{-2}
1	10.00	400.0	-	Foundation-ground spring	
2	10.00	-	-	Horizontal spring (kN/m)	1.789×10^6
3	8.90	140.0	-	Rotational spring (kN/rad)	2.019×10^6
4	3.75	206.3	-	Damping ratio	
5	0.00	-	-	Isolated bearing (%)	0
6	−1.00	227.5	876.8	Pier (%)	2
7	−2.00	-	-	Foundation-ground (%)	10

Table 2: Design parameters of HDR bearing [19]

Design parameter	HDR bearing
Cross-sectional area, A_e (mm^2)	480×480
Thickness of HDR, $\sum t_e$ (mm)	22×6
Compressive stress, σ (MPa)	3.40
Shear modulus, G (N/mm)	1.2
Equivalent stiffness, K_B (N/mm)	2,111.0
Design displacement, u_B (mm)	240

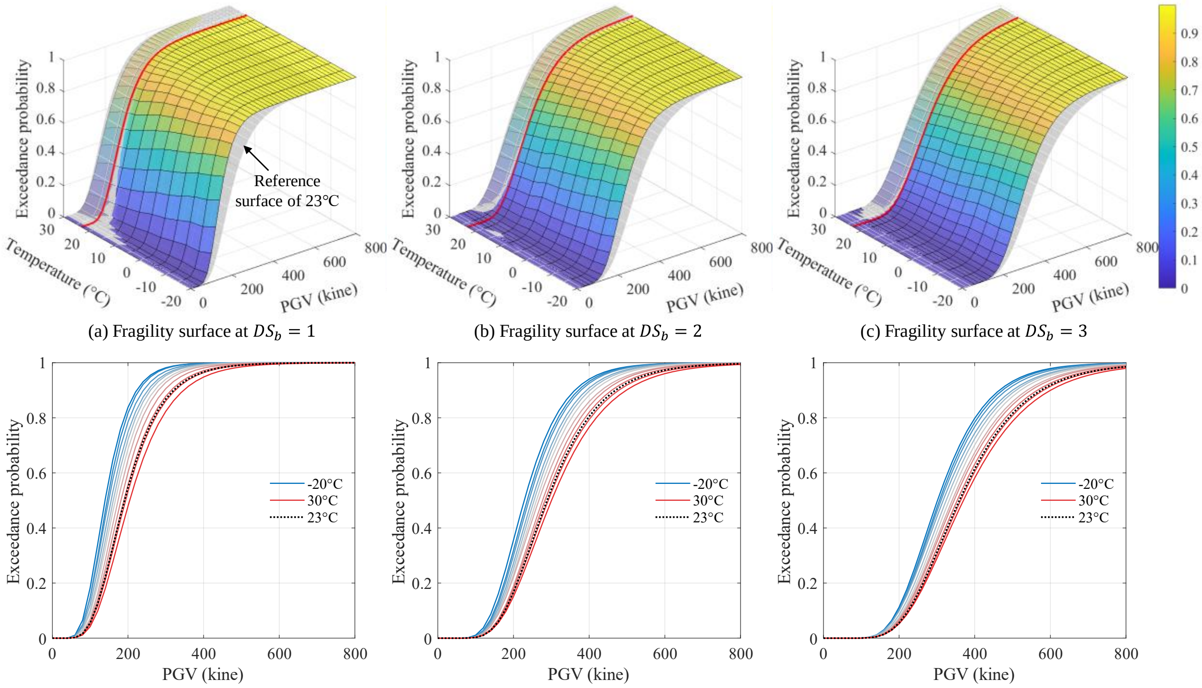
4 RESULTS AND DISCUSSION OF SEISMIC RISK ASSESSMENT IN COLD REGIONS

4.1 Dynamic and fragility analyses

A total of 80 recorded near-fault ground motions are selected for dynamic analysis. To ensure the diversity and characteristics of strong ground motion, the following criteria are applied: (1) the PGV of the ground motion is no less than 40 kine; (2) the PGA of the ground motion is no less than 250 gal; (3) the earthquake magnitude of the ground motion is no less than 6.0; (4) the maximum of two ground motions are selected from each seismic event. The PGV is selected as the IM in this case, ranging from 20 to 800 kine with an increment (ΔPGV) of 20 kine. Moreover, the increment of temperature measure (Δim) is set to 5°C.

The shear strain of the HDR bearing and the ductility of the bridge pier are selected as two engineering demand parameters (EDPs) in this case. Four damage states are defined for both the HDR bearing and the bridge pier: no damage ($DS = 0$), slight ($DS = 1$), moderate ($DS = 2$), and extensive ($DS = 3$). Note that the temperature effect is not directly considered in the seismic performance of RC pier, but is included in the HDR bearing. Assuming the stress for certain damage in the bearing is the same across temperatures, the strain for that damage at a certain temperature is the strain derived from the MTBW model using the stress for the same damage at ambient temperature.

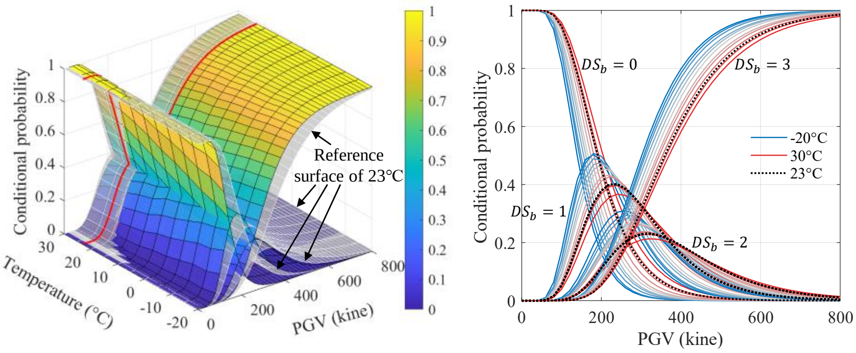
Figures 2 and 3 depict the fragility surface, curve, and conditional probability of the HDR bearing. A reference surface of 23°C, which represents the extended surface of the fragility curve calculated from room temperature, is compared with the fragility surface considering temperature effect in **Figure 2a-c** and **Figure 3a**. The intersection line of the two surfaces is highlighted with a red line. A reference dot line of 23°C is also marked in the fragility curve and conditional probability in **Figure 2d-f** and **Figure 3b**. Considering the temperature effect, a significant shift in the fragility surface is observed. This shift is also reflected in the fragility curves, where the probabilities of bearing reaching various DSs are increased notably at lower temperatures. Similarly, the fragility surface, curve, and conditional probability of the bridge pier are illustrated in **Figures 4 and 5**. Although the temperature effect is not directly considered in the pier, the temperature effect on the bearing indirectly raises the damage probability of the pier under low-temperature environments.



(a) Fragility surface at $DS_b = 1$ (b) Fragility surface at $DS_b = 2$ (c) Fragility surface at $DS_b = 3$

(d) Fragility curve at $DS_b = 1$ (e) Fragility curve at $DS_b = 2$ (f) Fragility curve at $DS_b = 3$

Figure 2: Fragility surface and curve of the HDR bearing



(a) Conditional probability face of DS_b (b) Conditional probability of DS_b

Figure 3: Conditional probability of the HDR bearing

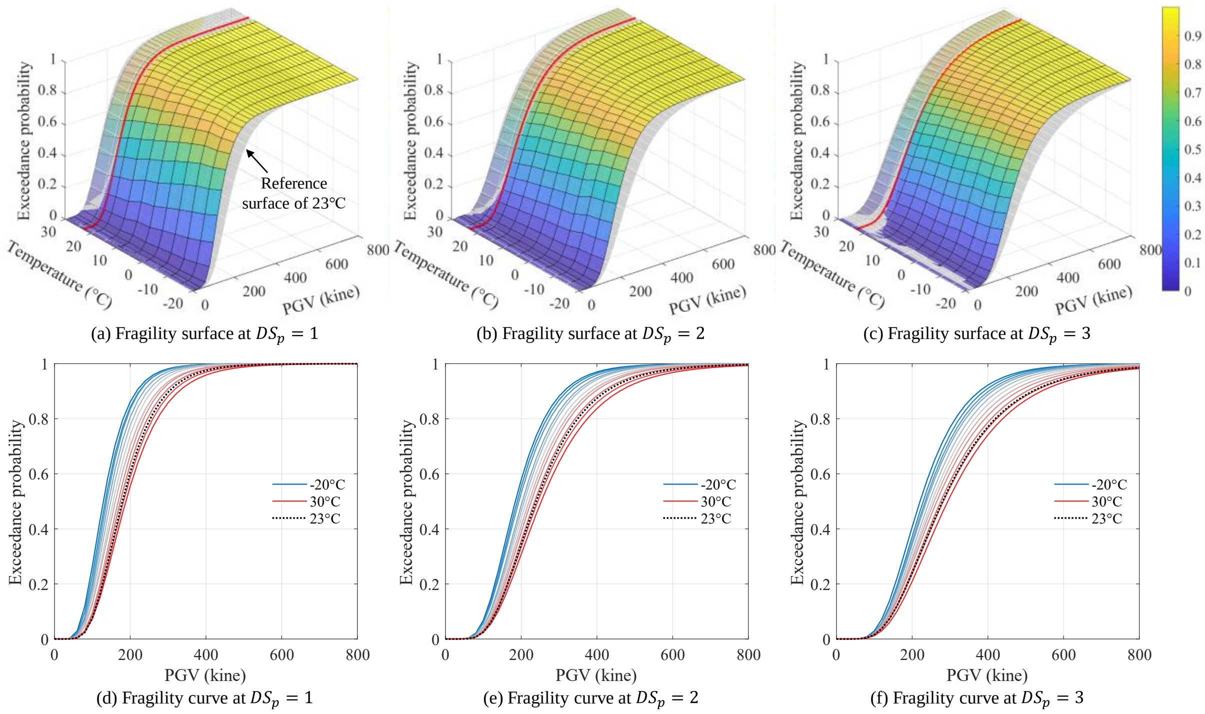
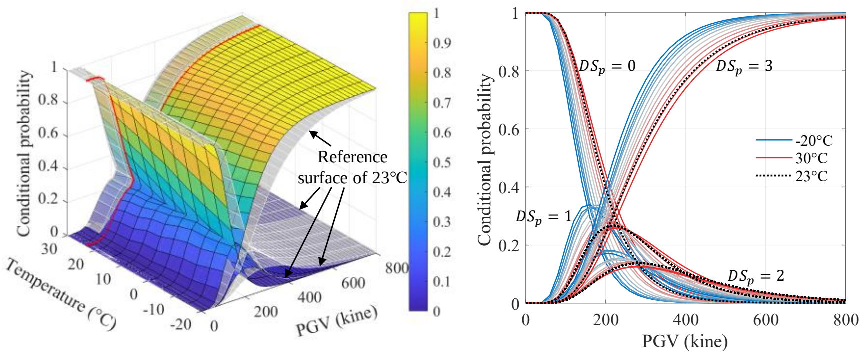


Figure 4: Fragility surface and curve of pier



(a) Conditional probability face of DS_p (b) Conditional probability of DS_p

Figure 5: Conditional probability of pier

4.2 Hazard and temperature distribution analyses

The bridge location is assumed to be a section of highway along the Kushiro Outer Ring Road in Hokkaido, Japan, as shown in **Figure 6** by Google Maps [22]. Kushiro, located in a seismically active zone, has experienced numerous strong earthquakes throughout history, which triggered tsunamis and caused significant damage to this region. The seismic hazard curve, estimated by an exponential function in **Eq. (3),** is shown in **Figure 7**.

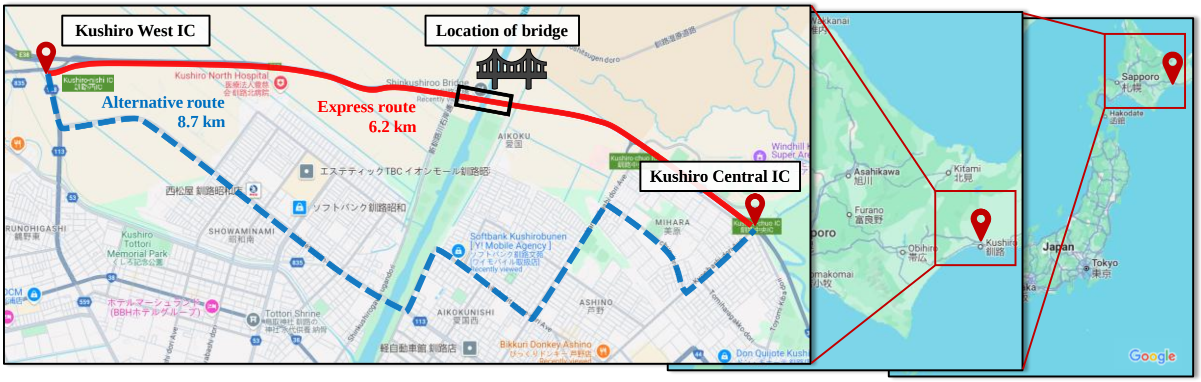


Figure 6: Location of bridge, express route, and alternative route

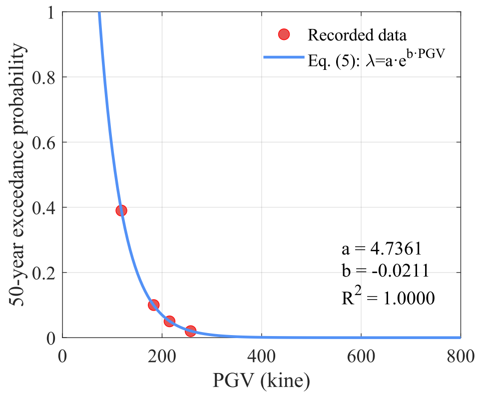


Figure 7: 50-year seismic hazard curve for location of bridge

To estimate the annual exceedance probability of hourly temperature at Kushiro, the hourly temperature data of Kushiro from 2020 to 2024 is collected from the meteorological records of JMA [23]. **Figure 8** illustrates the hourly temperature distribution in Kushiro over five years and its average value. The annual exceedance probability of hourly temperature is estimated by **Eq. (4)**, as shown in **Figure 9**.

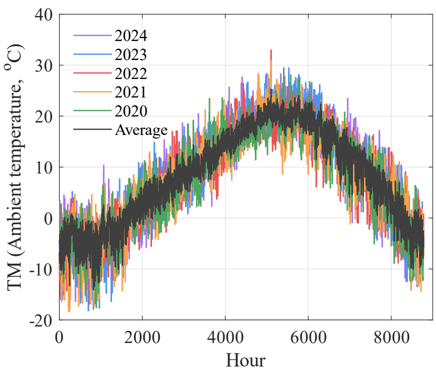


Figure 8 Hourly temperature distribution at Kushiro

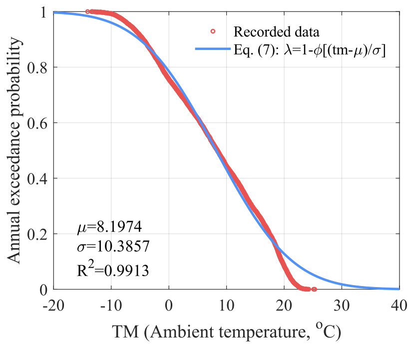


Figure 9 Annual exceedance probability of hourly temperature at Kushiro

4.3 Seismic damage probability estimation

The seismic damage probability can be estimated by the combination of the fragility function and the hazard curve and temperature distribution, according to **Eq. (7)**. **Table 3** lists the 50-year joint probability of seismic damage for the isolated bridge with various temperatures, with the combination of HDR bearing and pier. The probability without the consideration of temperature effect is also compared. **Figure 10** depicts the 50-year joint probability in the bar chart. It finds that after considering the temperature effect on components, the probability of no damage ($DS_b = 0$, $DS_p = 0$) significantly decreases from 0.681 to 0.598 by 8.3%. Correspondingly, the probability of various types of structural damage increases. This means that the isolated bridge is actually facing a higher risk of seismic-induced damage and loss.

Table 3 50-year joint probability of seismic damage for isolated bridge with temperature range of [−20℃, 30℃]

Joint probability $P(ds_{ij})$		HDR Bearing				Probability of pier
		$DS_b = 0$	$DS_b = 1$	$DS_b = 2$	$DS_b = 3$	
Pier	$DS_p = 0$	0.59805 (0.68067)	0.11265 (0.09926)	0.02305 (0.01895)	0.01606 (0.01328)	0.74981 (0.81215)
	$DS_p = 1$	0.11327 (0.09071)	0.02134 (0.01323)	0.00437 (0.00253)	0.00304 (0.00177)	0.14202 (0.10824)
	$DS_p = 2$	0.03386 (0.02446)	0.00638 (0.00357)	0.00130 (0.00068)	0.00091 (0.00048)	0.04245 (0.02918)
	$DS_p = 3$	0.05242 (0.04226)	0.00987 (0.00616)	0.00202 (0.00118)	0.00141 (0.00082)	0.06572 (0.05043)
Probability of bearing		0.79761 (0.83811)	0.15023 (0.12221)	0.03074 (0.02333)	0.02142 (0.01635)	1.00000

Note: The value in parentheses represents the joint probability without temperature effect.

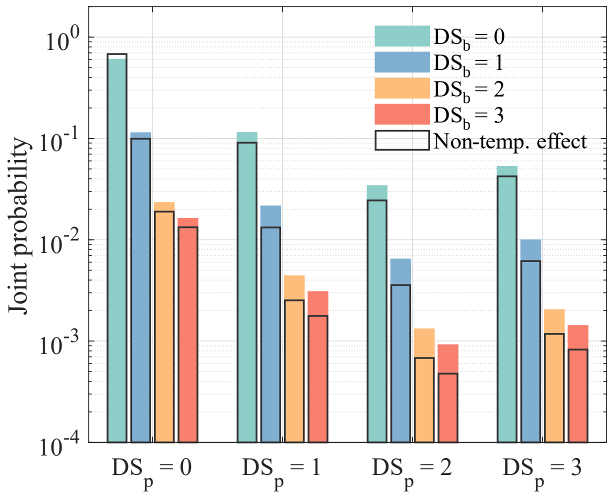


Figure 10 50-year joint probability of seismic damage for isolated bridge

5 CONCLUSIONS

- The temperature measure (TM) is introduced into the framework of seismic risk assessment due to the non-ignorable effect of temperature on the seismic performance of the isolated bridge with HDR bearings. By setting the damage state thresholds of temperature-sensitive components under different ambient temperatures, the temperature-dependent seismic performance of the component is evaluated, followed by the assessment of its failure probabilities under varying seismic intensities and ambient temperatures. The ambient temperature distribution is analyzed to obtain the annual exceedance probability of temperature, which is then used to estimate the seismic damage probability considering temperature variations.

- In dynamic and fragility analyses, compared with the non-temperature effect case, significant shifts in the fragility surfaces of the bearing and bridge are observed, indicating that the probabilities of the bearing and bridge reaching various damage states are increased notably at lower temperatures. In addition, as the ambient temperature decreases, the proportion of pier reaching DS=3 first increases slightly.
- In seismic damage probability estimation, 50-year joint probability of seismic damage of the isolated bridge is estimated. When considering the temperature effect, the probability of a bridge with no damage ($DS_b = 0$, $DS_p = 0$) decreases from 0.681 to 0.598 by 8.3%, while the probability of various types of structural damage increases accordingly. This means that the isolated bridge faces a higher risk of seismic-induced damage and loss.

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