

# Research on the Effects of Consolidated Ice on Seismic Performance of Offshore Bridge Pier

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**Keywords:** consolidated ice, bridge pier, seismic performance, ratio of collapse, collapse margin ratio

**Abstract.** Based on the simplified dynamic response calculation model of the bridge pier under the coupling effects of seismic loads and dynamic ice force, the effects of consolidated ice on the seismic performance of the bridge pier are studied. The results show that consolidated ice can even enlarge the maximum curvature of the bridge pier several times and generally enlarge the ratio of collapse more than 15%, especially under the far-field seismic waves. The Collapse Margin Ratio (CMR) of bridge pier surrounded by consolidated ice is significantly smaller than the acceptable CMR, which means the bridge pier surrounded by consolidated ice cannot meet the requirements of collapse-resistant capacity. It is necessary to consider the coupling effects of seismic loads and dynamic ice forces when design a bridge in icy water.

## Introduction

In high latitudes, there is a long frozen period every year and much of these areas are in earthquake-prone regions. The offshore engineering structures in the icy ocean are subject to both seasonal frozen and hydrodynamic pressure. In 1964 Alaskan earthquake, many bridges were destroyed due to seismic loads and ice forces. But there is still no specification of load combination of earthquake and ice loads when designing offshore engineering structures. The codes such as CSA (1992) [1] and API (1995) [2] only point that it is necessary to consider ice load, but it does not give the specific calculation method. Some researchers has focused the dynamic interaction of sea ice and structures under earthquakes, and put forward several ice force models based on field monitoring and experimental study [3-4]. Though such researches have some achievements of ice force models and their input in seismic analysis, the effects of sea ice on seismic response of structures are still ambiguous [5-6]. Therefore, it is still a challenge for experts how to design the offshore engineering being safety under the coupling action of ice forces and seismic loads.

The research developed a simplified calculation model of seismic analysis of bridge pier under the coupling action of ice forces and seismic loads, by considering hydrodynamic pressure as simplified added mass based on Morison Equation, and considering the dynamic interaction between sea ice and bridge pie as improved Croteau dynamic ice force model. The effects of ice on sea ice on nonlinear seismic responses of bridge pier will be clearly exposed and it provides the scientific reference for aseismic design and anti-ice design of bridge structures.

## Development of the calculation model of seismic analysis of structure-ice-water

In icy water, the offshore bridge pier is usually surrounded by ice, and the surrounded ice is called as consolidated ice because the ice connects with seacoast, shown as Fig.1. Under an earthquake, the bridge pier will be acted with both ice forces and earthquake loads, and the dynamic response analysis of the bridge pier involves structure-ice-water interaction. The hydrodynamic pressure on the pier is equal to the inertia force and damping force of added mass added on the pier under an earthquake [7]. In the simplified calculation model, the bridge pier is simplified as multi-mass system, upper structure is considered as lumped mass, hydrodynamic pressure is considered as added mass added on the pier, and the interaction of sea ice and pier structure is considered as mass and spring, shown as Fig.2.

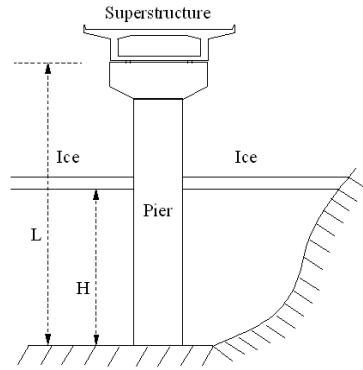


Fig.1 Simple sketch of the pier and ice

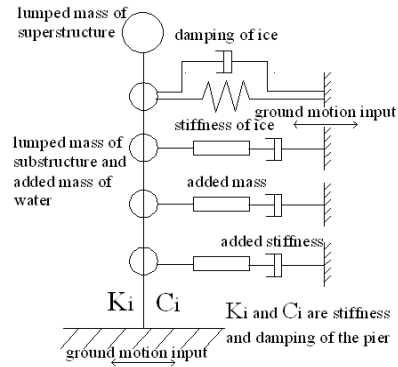


Fig.2 Simple calculation model of a bridge pier

Considering hydrodynamic pressure as added mass and considering the ice force as mass and spring, the dynamic equilibrium equation of pier structure subject to an earthquake is given as Eq.1

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{\ddot{y}\} - [K_{Ds}]\{\dot{x}\} \quad (1)$$

Where  $M$  is mass matrix,  $C$  is damping matrix,  $K$  is stiffness matrix,  $x$  is relative displacement response of pier structure,  $\ddot{y}$  is earthquake acceleration,  $K_{Ds}$  is resistance coefficient and  $K_{Ds} = \frac{1}{2}C_D r A_p$ .

The seismic hydrodynamic pressure can be simplified as added mass and additional resistance. The added mass added on the node can be calculated as Eq.2.

$$M_{ai} = \sum (C_M - 1) r S_{ij} l_{ij} \quad (2)$$

Where,  $S_{ij}$  is the area of upstream face of pier structure with a unit length,  $l_{ij}$  is half of the effective length of the element.

The additional resistance term of dynamic water is simplified as linear item, shown as Eq.3 [8].

$$\dot{x} \left| \dot{x} \right| = x_{rms} \sqrt{8/p} \dot{x} \quad (3)$$

Where,  $x_{rms}$  is root-mean-square value of velocity.

Withalm suggested the ice stiffness formula with considering structure size and ice crack, as shown in Eq.4 [9].

$$K = \left( \frac{1}{E_{eff} \cdot b} + \frac{4.58 - n}{p \cdot E \cdot h} \right)^{-1} \quad (4)$$

Where,  $E_{eff}$  is effective elastic modulus, and takes five percent of elastic modulus;  $b$  is the contact area of sea ice and the structure;  $n$  is the Poisson ratio.

The consolidated sea ice surrounding the pier is constrained by seacoast which is equivalent to a spring bearing of the bridge pier. So multiple-support excitation should be taken into account in the seismic analysis of bridge pier surrounded by consolidated sea ice. The seismic response of bridge pier is resulted by movement of bearings accompanying with time change. In the previous paper, the whole mathematic calculation process has been derived [9]. When the seismic time-histories loads are achieved, the seismic response of bridge pier surrounded by consolidated sea ice can be calculated by using *Newmark-β* method.

## Seismic analysis of bridge pier

### parameters of bridge pier and sea ice

The bridge pier surrounded with consolidated sea ice shown in previous paper is selected as the calculation model. In order to accurately assess the effects of consolidated ice on the seismic performance of bridge pier, the sufficient seismic waves with ample frequency spectrum were selected because the randomness of the earthquake influences the rationality of results much. Considering the ground motion parameters, such as epicentral distance and site soil condition and so

on, the plate boundary type seismic waves, hereinafter referred to as T1, and inland direct type seismic waves, hereinafter referred to as T2, both in Type II site and in Type III site as far-field seismic wave and near-field seismic wave respectively were used to seismic analysis, shown in Table 1.

Table 1 Characteristics of the seismic records

| Types of site condition | Type numbers | Earthquake names                  | Earthquake magnitude | Epicentral distance (km) | Record sites        | Peak accelerations ( $\text{cm/s}^2$ ) |
|-------------------------|--------------|-----------------------------------|----------------------|--------------------------|---------------------|--|
| Type II                 | T1-II-1      | 1968 Hyuga seismic wave           | 7.5                  | 100                      | Itashimahashi       | 362.617                                |
|                         | T1-II-2      |                                   |                      |                          |                     | 384.925                                |
|                         | T1-II-3      | Hokkaido-Toho-Oki Earthquake      | 8.1                  | 178                      | Onneto Bridge       | 364.849                                |
| Type III                | T1-III-1     | 1983 Nihonkai-Chubu Earthquake    | 7.7                  | 110                      | Tsugarushima        | 433.372                                |
|                         | T1-III-2     | 1994 Hokkaido-Toho-Oki Earthquake | 8.1                  | 268                      | Kushiro River levee | 424.006                                |
|                         | T1-III-3     | 1995 Great Hanshin earthquake     | 7.2                  | 30                       | Osaka gas station   | 438.520                                |
| Type II                 | T2-II-1      | 1995 Great Hanshin earthquake     | 7.2                  | 30                       | JR-Takatori station | 686.831                                |
|                         | T2-II-2      |                                   |                      |                          | Higashi-Kobe bridge | 672.639                                |
|                         | T2-II-3      |                                   |                      |                          | Port Island         | 736.334                                |
| Type III                | T2-III-1     | 1995 Great Hanshin earthquake     | 7.2                  | 30                       | Higashi-Kobe bridge | 591.034                                |
|                         | T2-III-2     |                                   |                      |                          | Port Island         | 557.427                                |
|                         | T2-III-3     |                                   |                      |                          | Port Island         | 619.186                                |

It is necessary to select proper earthquake intensity measures (IM) and structural damage measures (DM) in analysis seismic performance of structures. With the aims of analysis of the effects of consolidated sea ice on seismic performance of bridge pier subject to different types of seismic waves, the peak ground acceleration (PGA) is selected as IM and the curvature of bottom cross-section is selected as DM. If the curvature of the bottom cross-section is beyond the limit curvature, it means the bridge pier is destroyed.

#### *Effects of consolidated ice on seismic performance of the bridge pier*

The increment dynamic analysis (IDA) curves of bridge pier surrounded by sea ice subject to different seismic waves are shown in Fig.3. From results, it is clearly seen that the consolidated sea ice influences the seismic performance of the bridge pier significantly, especially under the far-field earthquakes. For example, under the T1-III-3 seismic wave, when the PGA is  $2\text{m/s}^2$ , the bridge pier is completely destroyed and the maximum curvature of the bottom cross-section is up to 0.0793, which is far above the limit curvature of the pier and is also 0.0757 bigger than the curvature corresponding to without ice.

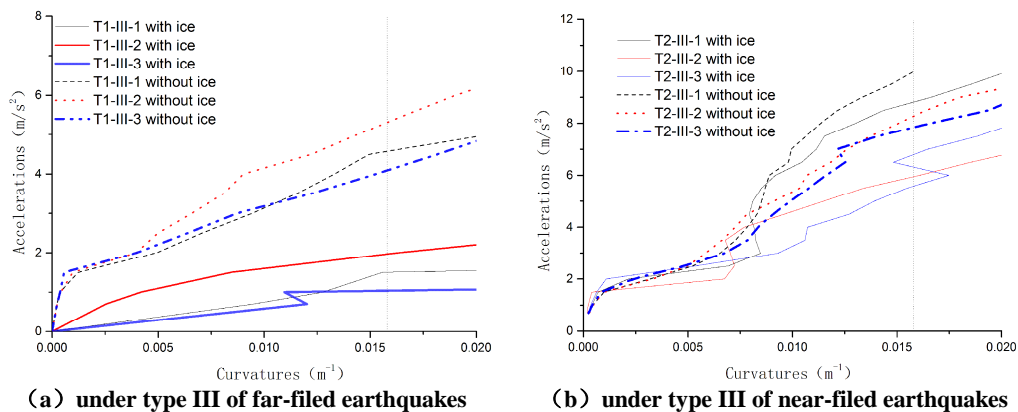


Fig.3 IDA curves of bridge pier surrounding with consolidated ice

With the PGA increasing, the effects of consolidated ice on the seismic performance are more remarkable. However, there is a little difference under near-field seismic waves. For example, under

type III near-field seismic waves, the curvatures of bridge pier surrounded by consolidated ice is smaller than that corresponding to without ice when PGA is small and bigger when PGA is big, which means there are restriction effects of consolidated ice when the PGA is small and there are enhancement effects when the PGA is big. So the effects of consolidated ice on seismic performance of the bridge pier under different earthquakes differ too much. It is necessary to select sufficient seismic waves with ample frequency spectrum to accurately valuate the effects of consolidated sea ice on seismic performance of a bridge pier.

Under different seismic waves, the effects of consolidated ice on the seismic fragility of the bridge pier are different. Taking rates of collapse, which is the ratio of the number of seismic records corresponding to bridge pier collapse to the number of total seismic records, as seismic fragility index, the seismic fragility curves of the bridge pier under different seismic waves are shown in Figure.7. With the PGA increasing, the rates of collapse increase no matter there is with consolidated ice surrounding the bridge pier or not. Without consolidated ice, the rate of 100% collapse occurs when the PGA is  $14\text{m/s}^2$ . However, the rate of collapse is remarkably bigger than that corresponding to without ice, which is general increase more than 15%. Therefore, the consolidated ice increases the seismic response of bridge pier and makes the bridge pier more fragile. Comparing the rates of collapse of the bridge pier subject to far-field seismic waves and near-field seismic waves, it can be seen that under a far-field earthquake, the effects of seismic fragility are more significant. Under far-field earthquake, the rate of 100% collapse occurs when PGA is  $4.5\text{m/s}^2$ , but under near-field earthquake, it occurs when the PGA is  $10\text{m/s}^2$ . So when design a bridge in icy water, it is necessary to consider the effect of sea ice on seismic performance of bridge pier subject to far-field earthquakes.

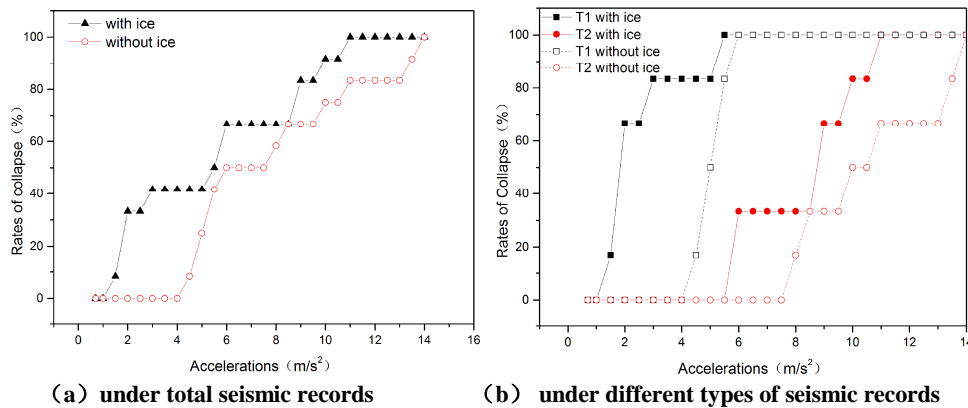


Fig.4 Fragility curves of the bridge pier surrounding with consolidated ice

The Collapse Margin Ratio (CMR) which indicates the relationship between the actual collapse-resistant capacity and the design collapse-resistant capacity of structures according ATC-63, is used to study the effects of consolidated ice on the seismic performance of the bridge pier. The CMR is defined as the ratio of the PGA, corresponding to 50% of the seismic waves under which the bridge pier collapses, to the design PGA, shown as Eq.5. In order to ensure the rate of collapse of bridge pier under strong earthquake is below 10%, the acceptable CMR is 2.55 in the paper.

$$\text{CMR} = \frac{\text{PGA}_{50\%}}{\text{PGA}_{\text{design}}} \quad (5)$$

Where,  $\text{PGA}_{50\%}$  is the earthquake intensity corresponding 50% of the seismic waves cause bridge pier collapse, and  $\text{PGA}_{\text{design}}$  is the maximum earthquake intensity for the bridge pier design.

When there is no sea ice, the CMR is 3.06. But when the bridge pier is surrounded by consolidated ice, the CMR is 2.31, which is significantly smaller than the acceptable CMR. So it means that the bridge pier surrounded by consolidated ice cannot meet the requirements of collapse-resistant capacity. And it also demonstrates that the consolidated ice has great effects on seismic performance of bridge pier surrounded by consolidated ice. When design a bridge in icy water, it is necessary to consider the coupling effects of seismic loads and dynamic ice forces.

## Conclusions

The consolidated ice has great effects on seismic performance of the bridge pier. The rates of collapse are obviously bigger than those corresponding to without ice, which can generally increase more than 15%. Meanwhile, the effects are more remarkable when the bridge pier subject to far-field earthquakes. But under near-field earthquakes, there are restriction effects of consolidated ice when the PGA is small and there are enhancement effects when the PGA is big.

Comparing without ice, The CMR of bridge pier surrounded by consolidated ice is significantly smaller than the acceptable CMR, which means that the bridge pier surrounded by consolidated ice cannot meet the requirements of collapse-resistant capacity. With the aim of safe operation of bridge pier in icy water, it is necessary to select sufficient seismic waves with ample frequency spectrum to accurately valuate the effects of consolidated sea ice on seismic performance of a bridge pier.

## Acknowledgements

This work was financially supported by the scientific research foundation project of by Civil Aviation University of China (No. 2013QD15S), the Young Teacher Foundation of Civil Aviation University of China (No. 10700601), and the Fundamental Research Funds for the Central Universities (No. 3122017053).

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