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Overview of Japanese Road Bridge Design Code: Specifications for Highway Bridges – Focus on foundation design

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Abstract: In accordance with international reliability-based design codes, Japanese road bridge design code titled "Specifications for Highway Bridges (SHB)" was revised as a complete performance-based design code, and a reliability-based design code in 2017. The features of Japanese road bridge design, for example, performance requirements with considering earthquakes, a tremendous amount of experiences for preserving bridge safety, are reflected in this code. Furthermore, load resistance factor design (LRFD) is adopted for limit state design in this revised code. This paper provides an overview of the revised SHB, such as performance requirements for road bridges, performance matrix, design situations, verification of the performance requirements, determination of resistance factors, etc.

Keywords: Specifications of Highway Bridges (SHB); performance requirements; LRFD; resistance factors; foundations.

1 Introduction

Reliability-based design codes such as Eurocode and AASHTO-LRFD have been developed around the world. Meanwhile, ISO2394, which is the basis of the development of reliability-based design codes, was also revised in 2015. In view of this, Japanese road bridge design code titled "Specifications for Highway Bridges (SHB)" was revised as a complete performance-based design code, and a reliability-based design code (JRA 2017).

SHB stipulates the design of bridges that satisfy performance requirements with enough reliability throughout their working lives (100 years). Performance under load-resistance conditions and durability are the requirements of bridge design. Durability performance ensures the load-resistance performance of a bridge until the end of the designed working life by considering time-related deterioration of the components of the bridge. Load-resistance performance of a bridge is verified by using the strength that ensures that the bridge lasts for 100 years. The maintenance design ensures the strength that is necessary for satisfying this requirement. Furthermore, road bridges are required to maintain conformity performance such that any damage to the bridge does not affect users, and vibration and noise that the bridge makes do not adversely affect users and the surrounding environment. The conformity performance is verified from the specifications obtained from a large body of data based on experiences of road bridge design and construction in Japan.

For load-resistance performance verification, SHB provides two verification methods, approach A and B. In approach A, the designer directly verifies whether or not a target bridge satisfies the performance requirements by using appropriate methods. In approach B, the satisfaction of performance requirements is verified from the state of the members that compose the bridge by using the specifications described in this SHB. If the bridge is verified using approach B, it is deemed to satisfy the performance requirements. Here, the state of the members is called the load-resistance performance of the members in the approach B. In other words, the load-resistance performance of a bridge is verified by the load-resistance performance of its members. The foundation of the bridge is also treated as one of the members. Approach B is generally adopted in design practice. Load and resistance factor design (LRFD) was adopted as the format of level 1 reliability-based design for approach B. The partial factors to verify load-resistance performance of bridges in approach B are defined from the Japanese database, such as the results of vertical and horizontal pile loading tests etc. in the case of foundation design.

This paper focuses on foundation design and introduces verification points for stability, the load-resistance performance verification in approach B, a determination example of partial factors concerning resistance based on both uncertainties and experiences, and the verification of conformity performance, as well as design situations and performance matrices in SHB, which are explained from the viewpoint of the authors' understanding of SHB (they are not official comments of code writers and JRA).

2 Design Situations (Action Combinations)

SHB provides three design situations for the verification of load-resistance and conformity performance: dominant situations of permanent actions (DS-1), variable actions (DS-2), and accidental actions (DS-3).

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Permanent action means that the action occurs with high frequency and its time-fluctuation range is small compared with the mean value, self-weight of structure, pre-stressed force and environmental action for instance. Variable action means that the action occurs frequently and its fluctuation is not negligible, for example live loads, wind loads, and level 1 earthquakes. Level 1 earthquakes are high-probability ground motion and they are categorized under variable actions. Accidental action means that the action occurs rarely but its effect on the bridge and on the population in general is large. Examples are collision force and level 2 earthquakes. Level 2 earthquakes are low-probability ground motion but large earthquakes and it is categorized under accidental actions. Table 1 presents concrete action combinations used in the verification of load-resistance performance. The action in a parenthesis is combined as necessary to consider the most unfavorable condition of the bridge.

Table 1. Action combinations used in the verification of load-resistance performance.

1. Dominant situations of permanent actions (DS-1)	
(1)	D + PS + CR + SH + E + HP + (U) + (TF) + GD + SD + WP + (ER)
2. Dominant situations of variable actions (DS-2)	
(2)	D + L + I + PS + CR + SH + E + HP + (U) + (TF) + (SW) + GD + SD + (CF) + (BK) + WP + (ER)
(3)	D + PS + CR + SH + E + HP + (U) + TH + (TF) + GD + SD + WP + (ER)
(4)	D + PS + CR + SH + E + HP + (U) + TH + (TF) + GD + SD + WS + WP + (ER)
(5)	D + L + I + PS + CR + SH + E + HP + (U) + TH + (TF) + (SW) + GD + SD + (CF) + (BK) + WP + (ER)
(6)	D + L + I + PS + CR + SH + E + HP + (U) + (TF) + GD + SD + (CF) + (BK) + WS + WL + WP + (ER)
(7)	D + L + I + PS + CR + SH + E + HP + (U) + TH + (TF) + GD + SD + (CF) + (BK) + WS + WL + WP + (ER)
(8)	D + PS + CR + SH + E + HP + (U) + (TF) + GD + SD + + WS + WP + (ER)
(9)	D + PS + CR + SH + E + HP + (U) + TH + (TF) + (SW) + GD + SD + WP + EQ + (ER)
(10)	D + PS + CR + SH + E + HP + (U) + (TF) + GD + SD + WP + EQ + (ER)
3. Dominant situations of accidental actions (DS-3)	
(11)	D + PS + CR + SH + E + HP + (U) + GD + SD + EQ
(12)	D + PS + CR + SH + E + HP + (U) + GD + SD + CO

Here, D is the dead load, PS is the pre-stressed force, CR is creep effects in concrete, SH is the shrinkage effect in concrete, E is the earth pressure, HP is the hydraulic pressure, U is the buoyancy or uplift, and TF is the effect of temperature changes, GD is the effects of ground deformation, SD is the effects of support moving, WP is the wave pressure, ER is the load in construction, L is the live load, I is the effects of impact, SW is the snow load, CF is the centrifugal load, BK is the braking load, TH is the effects of temperature change, WS is the wind load acting to the bridge, WP is the wind load with respect to live load, EQ is the effect of earthquake, CO is the collision load.

3 Performance Matrices for Bridges

SHB provides two load-resistance performances, one for ordinary bridges and one for important bridges, as shown in Table 2. "Satisfaction" in the table means that the required state of the bridge is satisfied with the required reliability. As a point of special mention of the performance matrices of SHB, the function that the "bridge partially loses bearing ability of loads but is in the extent of specific bearing ability of loads" is required for important bridges in DS-3. The aim of the function can be interpreted as follows. If the bridge is built as a part of an emergency transportation road, it should be usable after a large earthquake in the function, because it is necessary for emergency relief work and recovery from the disaster.

Table 2. Matrices of load-resistance performance for bridges.

	Bridge state for function		Bridge state for safety
	Bridge dose not lose bearing ability of loads	Bridge partially loses bearing ability of loads but is in the extent of specific bearing ability of loads	Bridge does not become destructive state
Load-resistance performance-1 (for ordinary bridge)			
DSs-1 & 2	Satisfaction	-	Satisfaction
DS-3	-	-	Satisfaction
Load-resistance performance-2 (for important bridge)			
DSs-1 & 2	Satisfaction	-	Satisfaction
DS-3	-	Satisfaction	Satisfaction

4 Verification Points for Stability of Foundation in Approach B

In approach B, the abovementioned load-resistance performance for bridges has to be verified from load-resistance performance of members that compose the bridge. Table 3 presents verification points for stability of foundation with respect to load-resistance performance as well as conformity performance.

Table 3. Verification points for foundation.

	Conformity performance			Load-resistance performance		
Load / Foundation type	Vertical load	Horizontal load	Overturning moment	Vertical load	Horizontal load	Overturning moment
Spread foundation	X	X	X	X	X	X
Pile foundation	XX	X	-	XX	X	-
Caisson foundation	X	X	-	X	X	-
Steel-pipe-sheet-pile foundation	XX	X	-	XX	X	-
Cast-in-situ diaphragm wall foundation	X	X	-	X	X	-
Mountainous foundation*	X	X	-	X	X	-

XX: the foundation is verified by not only pushing force but also pulling force.
Mountainous foundation: vertical shaft diameter is larger than 2.0 m, which is manually constructed in the mountainous area.

5 Verification of Load-Resistance Performance in Approach B

5.1 Limit states

SHB provides three limit states, 1, 2, and 3. These are defined properly for the members that compose the bridge in accordance with load-resistance performance of the bridge. Figure 1 shows the concept of the respective limit states. Limit state 1 deals with ensuring that the response of a member is in reversible extent. Namely, the yield limit characteristic value of the member is defined. For example, in case of the bearing capacity verification of a pile foundation for DS-1, the characteristic value of the yield bearing capacity of the pile is determined as limit state 1. Limit state 2 ensures energy absorption by recursive behavior of the part that the designer considers non-linear. Limit state 3 ensures that the bridge does not enter the destructive state. In other words, limit state 3 is defined from the state in which the strength of a member starts decreasing. In the verification of load-resistance performance of the members that compose a bridge, the responses of the members have to be verified so that they do not exceed both limit state 1 for the function requirement and limit state3 for the safety requirement in DCs-1 and 2. Furthermore, in the case of DC-3, if it is an ordinary bridge, the responses are verified so that they do not exceed only limit state 3 for the safety requirement. However, if it is an important bridge, the responses will have to be verified not to exceed both limit state 2 for the function requirement and limit state 3 for the safety requirement.

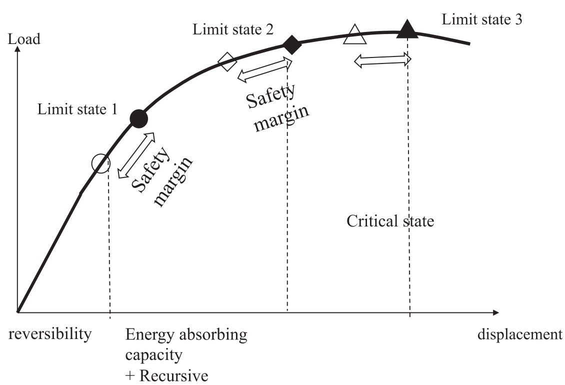


Figure 1. Concept of respective limit states

5.2 Verification of foundation for load-resistance performance

The verification of members that compose the foundation for load-resistance performance is conducted by confirming that Eqs. (1) and (2) are satisfied.

$$\text{Limit state 1, 2: } \Sigma S_i (\gamma_{pi}\, \gamma_{qi}\, P_i) \leq \xi_1\, \Phi_R\, R \tag{1}$$

$$\text{Limit state 3: } \Sigma S_i (\gamma_{pi}\, \gamma_{qi}\, P_i) \leq \xi_1\, \xi_2\, \Phi_R\, R \tag{2}$$

Here, S_i is the action effect, P_i is the characteristic values of actions, γ_{qi} is the load combination factor, and γ_{pi} is the load factor. ξ_1, ξ_2, and Φ_R are the partial factors multiplying the characteristic value of the member resistance R, and Φ_R is the resistance factor. The uncertainties of the member resistance, such as the estimation error of the real ultimate bearing capacity obtained from the pile-loading test by using design equation, are considered in Φ_R. ξ_1 is a partial factor concerning survey and analysis obtained by considering the uncertainties of the estimation of member responses, stress and displacement. ξ_2 is a factor obtained by considering the uncertainties of residual strength magnitude after the member yields. ξ_2 is used only in the verification of limit state 3.

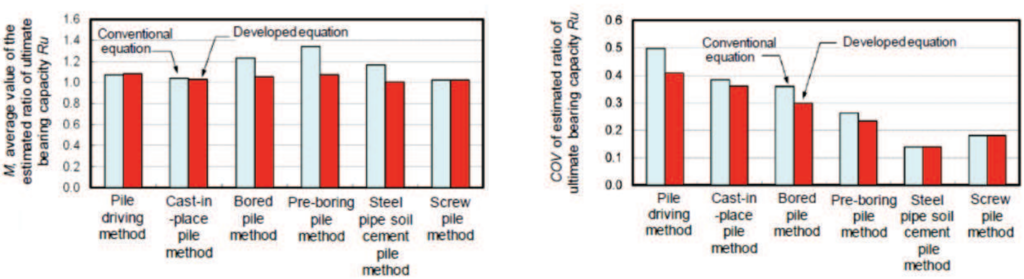
6 Determination of Partial Factors Concerning Resistance Based on Uncertainties and Experiences

Partial factors concerning resistance are generally determined by considering the several uncertainties from the database. The Japanese database, however, is not enough to determine all the partial factors in SHB. Therefore, there are many cases in which the partial factors concerning resistance are determined by considering both uncertainties and a large body of data based on experiences of road bridge design and construction in SHB. This section introduces an example of determining partial factors of ξ_1, Φ_R for the restriction value estimation of pushing force for a pile foundation in limit state 1, given by Eq. (3), by considering uncertainties and experiences as a feature of SHB.

$$R_d = \xi_1\, \Phi_R\, \lambda_f\, \lambda_n\, (R_y - W_s) + W_s - W \tag{3}$$

Here, R_d is the restriction value of pushing force (kN), λ_f is a factor obtained by considering bearing type of the pile foundation. λ_n is a factor obtained by considering the difference of resistance character that depends on pile numbers (1.0 is used as a standard value), R_y is the characteristic values of the yield bearing capacity that is determined from the ground (kN), W_s is the effective weight of the soil replaced by the pile (kN), and W is the effective weight of the pile and the interior soil of the pile, (kN).

Figure 2 shows the reproducibility of ultimate bearing capacities obtained from pile loading tests by using design equations (Nanazawa et al. 2019). SHB provides six design equations of the ultimate bearing capacity of the pile, which depend on the construction methods of the pile, namely, the cast-in-place concrete pile, driven pile, bored pile, pre-boring pile, steel pipe-soil cement composite pile, and screw pile (rotation penetration steel-pipe pile with one or two wings at the tip). In Figure 2, “conventional equation” and “developed equation” refer to the previous SHB and one of revised SHB, respectively. According to the figure, coefficient of variations (COVs) of cast-in-place concrete pile, driven pile and bored pile are large compared with others. Therefore, difference of the uncertainties has to be considered to determine partial factors. However, the fact that there has never been a defect in the three piles (cast-in-place concrete pile, driven pile, and bored pile) from the viewpoint of bearing capacity obtained from a large data-set from experiences of building piles designed by previous SHB should also be considered. Hence, it was considered that the three piles have enough safety with respect to bearing capacity and the values of partial factors ξ_1= 0.90 and Φ_R = 0.80 were determined for the three piles by back analysis of the previous SHB.



(a) Mean value (b) Coefficient of variation

Figure 2. Uncertainty of the bearing capacity of the piles.

The partial factors for the other three piles, namely, the pre-boring pile, steel pipe-soil cement composite pile and screw pile, were determined as ξ_1= 0.90 and Φ_R = 0.90 by considering their small COVs. Additionally, because the COV's effect to the foundation responses, stress, and displacement, was not confirmed from the analysis result, the partial factor of ξ_1 for all piles is determined to be 0.90.

7 Verification of Conformity Performance

As mentioned in the introduction, road bridges have to conform to fundamental items in SHB. This means that any damage to the bridge as well as vibration and noise that it makes should not affect users and surrounding environment. This verification has been carried out on road bridge design for several decades and is based on long experience of road bridge design and construction in Japan. In the process of SHB revision, the verification qualitatively contributes to the design of a usable road bridge. Therefore, the verification is also implemented in the revised SHB and is called conformity performance.

The verification is conducted to prevent the occurrence of large permanent displacement and settlement in a bridge. The verification points for conformity performance from the viewpoint of foundation are described in Table 2 with one for load-resistance performance. The action combinations described in Eq. (4) and Eq. (5) are used in the verification.

Action combination 1 (AC1):

$$1.0\ (D + L + PS + CR + SH + E + HP + (U)) \tag{4}$$

Action combination 2 (AC2):

$$1.05D + 1.05PS + 1.05CR + 1.05SH + 1.05E + 1.05HP + 1.05U + 1.00TF \tag{5}$$

AC1 is used only for this verification. Meanwhile, AC2 is also used for the verification of load-resistance performance as well as one of this verification. The restriction value is stipulated depending on respective members and foundations that compose the bridge. For example, in case of spread foundation, the vertical subgrade reaction does not exceed the restriction value described in Table 4.

Table 4. Restriction vertical subgrade reaction for spread foundation.

Bearing layer		Restriction value (kPa)
Clayey		200
Sandy		400
Sandy with gravel		700
Hard rock	Few crack	2500
	Many crack	1000
Soft rock		600

8 Conclusions

This paper presented an overview of the Japanese road bridge design code, "Specifications for Highway Bridges (SHB)" with focusing on foundation design, which was revised as a complete performance-based design code and reliability-based design code in 2017. The following conclusions can be drawn:

- Three performances, load-resistance and durability for preserving bridge function and safety, and conformity to fundamental items, as a road bridge for achieving usable road bridge, are required for bridge design.
- Two verification methods, approach A and B, are provided for load-resistance performance verification.
- In approach B, the load-resistance performance of bridges is verified from the state of members that compose the bridge.
- Three design situations (DSs), DS-1, 2, and 3, are provided for load-resistance performance verification.
- Two performance matrices, for ordinary and important bridges, are provided for load-resistance verification.
- Verification points for load-resistance performance verification of foundations by approach B are described as well as those for conformity performance verification.
- Three limit states (LSs), LS-1, 2, and 3, are provided for load-resistance performance verification.
- LRFD is adopted as the format of level 1 reliability-based design for approach B.
- In many cases, resistance side partial factors are determined from both uncertainties and experiences. Therefore, an example of the determination was described.

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