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Design of foundation structures of sea-crossing bridges on serviceability limit state

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Abstract: The target reliability indices of the foundation structures of sea-crossing bridges on the serviceability limit state (SLS) are different from those of common bridges due to their different surroundings. Consequently, three levels of the target reliability indices, which are 1.5, 2.0 and 2.3, respectively, for those structures on the SLS are suggested based on the Joint Committee on Structural Safety (JCSS) model code, and a new method of calibrating factors of live loads, which is based on the contribution ratio of tensile stresses of reinforcing bars produced by various loads to the maximum crack width of concrete, is proposed. Finally, the calibration of the reliability-based factors of the frequent value and the quasi-permanent value of live loads is conducted by the Joint Committee (JC) method through an actual design, and the indices are proved to be reasonable and the new method is proved to be feasible.

Key words: sea-crossing bridges; target reliability; JC (Joint Committee) method; frequent value; quasi-permanent value; foundation structures

Design code plays a central role in the building process because it specifies the requirements that designers must satisfy to attain the minimum acceptable performance level[1]. Currently, the goal of structural performance has been extended. Not only the ultimate limit state (ULS)-flexural failure, shear failure, and collapse, but also serviceability limit state (SLS)-cracking, durability, deflection, and vibration must be considered in the structural design and analysis. The SLS design is becoming more important since sometimes it would dominate the design according to actual design experiences. However, compared with the ULS design the development of the SLS design is deficient, especially for some special structures like sea-crossing bridges. Then specific analysis is needed since there are no corresponding specifications in relevant codes.

"How safe is safe enough" is the question that should be dealt with first in any design codes. In other words, acceptable safety levels must be established for various design situations covered by the codes. These levels, implicitly expressed in terms of target reliability indices but distinctly expressed in terms of load and resistance factors in reliability-based design codes, serve as a basis for the development of design criteria. Identically, the acceptable serviceability levels may also be expressed in terms of some reliability-based factors such as the factors of the frequent value and the quasi-permanent value of live loads.

As a special structure, a sea-crossing bridge is always a long-span bridge. Sometimes, the SLS design would govern the design of the foundation structures of a sea-crossing bridge. In the crack width of the SLS design, the representative values of live loads are frequent values for load combinations of short-term effects and quasi-permanent values for load combinations of long-term effects. This includes the values for load combinations of short-term effects influenced by that of long-term effect according to the code JTG D62—2004. The environmental loads such as wind, wave and current loads acting on these bridges are generally high and change enormously, and always become the dominant loads, which is totally different from that acting on common bridges. Consequently, the implicit target reliability indices and the corresponding factors of live loads in the current code of highway bridges may not be suitable for this kind of structure. These indices and factors should thus be necessary to re-calibration based on its own specialties such as information of its design and environments.

The reliability-based factors of the frequent values and the quasi-permanent values of live loads can be obtained by many times of tentative calculations with the first-order reliability method (FORM). The conventional SLS function of highway bridges, which is similar to the ULS function, is defined as

$$Z = R - S = 0 \tag{1}$$

where S is the load effect, a stochastic parameter which represents the observed maximum crack width or the deformation of structural components, and R is the structural resistance which represents the allowable crack width or deformation. R may be a stochastic parameter which needs sufficient statistical data, but there is usually a lack of information. However, R can be regarded as a constant in many cases. The calculation of reliability on the SLS with the FORM can easily be carried out when the parameters of S and R have been obtained[2]. However, it is too difficult to set up a feasible SLS function directly with the perspective of crack width for foundation structures of sea-crossing bridges because of lack of experiences of similar projects and lack of various statistical data. An alternative way must thus be developed.

1 Design and Analysis of Foundation Structures of Sea-Crossing Bridges on SLS

1.1 Applicability of the factors of live loads in the current code

The crack width of concrete components can be calculated

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as[3]

$$W_{\mathrm{fk}} = C_1 C_2 C_3 \frac{\sigma_{\mathrm{ss}}}{E_{\mathrm{s}}}\left(\frac{30+d}{0.28+10\rho}\right) \tag{2}$$

where E_s, d, σ_{ss} and ρ are the Young's modulus, the diameter, the stress with load combinations of short-term effects, and the ratio of reinforcement of longitudinal tensile reinforcing bars, respectively. C_1 is the surface-shape factor of reinforcing bars, C_3 is the force-type factor, and C_2 is the influence coefficients with load combinations of long-term effects and can be described as

$$C_2 = 1 + 0.5 N_{\mathrm{L}}/N_{\mathrm{s}} \tag{3}$$

where N_s and N_L represent component forces with load combinations of short-term effect and long-term effect, respectively, and are given as

$$N_{\mathrm{s}} = \sum_{i=1}^{m} S_{\mathrm{G}ik} + \sum_{j=1}^{n} \psi_{\mathrm{s}j} S_{\mathrm{Q}jk} \tag{4}$$

$$N_{\mathrm{L}} = \sum_{i=1}^{m} S_{\mathrm{G}ik} + \sum_{j=1}^{n} \psi_{\mathrm{L}j} S_{\mathrm{Q}jk} \tag{5}$$

where S_* represents the nominal value of each load, ψ_{sj} and ψ_{Lj} are the factors of the frequent value and the quasi-permanent value of the j-th live load, respectively, and both adopt 0.75[4] for wind load. The design of one pile of one sea-crossing bridge is taken as an example to show the comparison (see Tab. 1) between the current code and the old code.

Tab. 1 Comparison of reinforcing bars in one pile of one sea-crossing bridge

Code	State of calculation	Diameter/mm	Quantity
JTG D62—2004	Bearing capacity	40	103
	Short-term effect influenced by long-term effect	40	153
JTJ 023—85	Bearing capacity	40	73
	Short-term effect	40	96

According to the API code[5], the load combination of wind, wave and current on the ULS for an offshore jacket platform follows

$$0.8(1.4F + 1.4W) = 1.12(F + W) \tag{6}$$

where F and W are the nominal values of wave current load and wind load, respectively. It takes 2.8[6] as the target reliability index for components of offshore jacket platforms through some calibrations of different sea areas with Eq. (6). For the foundation structures of sea-crossing bridges in the same offshore environments, the load combinations of wind, wave and current with short-term effects influenced by long-term effects on the SLS is given as[3]

$$0.75(F+W)\left(1+0.5\frac{N_{\mathrm{L}}}{N_{\mathrm{s}}}\right) = 0.75(F+W)\cdot \left[1+0.5\frac{0.75(F+W)}{0.75(F+W)}\right] = 1.125(F+W) \tag{7}$$

The partial factors of design loads directly relate to the degree of corresponding target reliability. Evidently, the target reliability index that corresponds to the factors of the frequent value and the quasi-permanent value of live loads obtained by the current code of highway bridges is near to 2.8 because the reliability index related to Eq. (7) is close to that related to Eq. (6). It is bigger than the upper bounds of 1.0 to 2.0[7] which is the range of the reliability index for concrete components of common bridges on the SLS, and even close to the target reliability index of the foundation structures of common bridges on the ULS[8]. The minimum target reliability index of bridges on SLS varies from 0.8 to 1.0 according to the code JTJ 023—85.

Consequently, the target reliability index implicitly expressed in the current code of highway bridges is obviously too high for the design of foundation structures of sea-crossing bridges. It can confuse engineers due to the large variations in amounts of engineering materials designed by the current code and the old code. It is thus necessary to suggest a more appropriate target reliability index for sea-crossing bridges and the corresponding reliability-based factors of live loads.

1.2 Comparison of factors of wind load with different codes

If the ratio of wind load effect W to dead load effect G is δ, C_2 can then be formulated as

$$C_2 = 1 + 0.5\frac{G(1+\psi_{\mathrm{L}}\delta)}{G(1+\psi_{\mathrm{s}}\delta)} = 1 + 0.5\frac{1+\psi_{\mathrm{L}}\delta}{1+\psi_{\mathrm{s}}\delta} \tag{8}$$

where factor C_2 only relates to ψ_L, ψ_s and δ. Define factor C

$$C = C_2(1+\psi_{\mathrm{s}}\rho) \tag{9}$$

as the factor of the crack width with load combinations of short-term effects influenced by long-term effects. Suppose that the wind load is the dominant load. The values of C_2 and C are different within the ordinary ratio of load effects due to different factors of the frequent value and the quasi-permanent value of live loads among the codes of JTG D60—2004, GB 50009—2001 and DIN-Report101 (German) (see Tab. 2). It is evidently conservative to calculate the crack width of concrete components of foundation structures of sea-crossing bridges with the factors of wind loads in the code JTG D60—2004.

Tab. 2 Comparison results of factors C_2 and C with different codes

Code	ψ_s	ψ_L	Factors	δ							
				0.0	0.5	1.0	1.5	2.0	3.0	4.0	5.0
JTG D60—2004	0.75	0.75	C_2	1.500	1.500	1.500	1.500	1.500	1.500	1.500	1.500
			C	1.500	2.062	2.625	3.188	3.750	4.875	6.000	7.125
GB 50009—2001	0.4	0.0	C_2	1.500	1.417	1.357	1.313	1.278	1.227	1.192	1.167
			C	1.500	1.700	1.900	2.100	2.300	2.700	3.100	3.500
DIN-Report101	0.5	0.0	C_2	1.500	1.400	1.333	1.286	1.250	1.200	1.167	1.143
			C	1.500	1.750	2.000	2.250	2.500	3.000	3.500	4.000

1.3 Analysis of the factors of wind load for one sea-crossing bridge

Both the frequent value and the quasi-permanent value of live loads can be expressed in terms of the representative values with some threshold exceedance rate during the design reference period. E. g., the former corresponds to values of 5% of the threshold exceedance rate, and the latter corresponds to values not exceeding 50% of that[9-10]. According to statistical analyses of actual wind velocity from the reports of wind parameters research for one sea-crossing bridge, the deductive monthly extreme wind velocity at the site of the bridge can be obtained. Then simulated wind velocities at a 100-year design reference period and statistical analysis of corresponding threshold exceedance rates can be obtained through the Monte-Carlo simulation (see Fig. 1). It can be found that $V_{0.05}$ and $V_{0.5}$, the wind velocities at 5% and 50% of the threshold exceedance rate, are 32.597 m/s and 26.223 m/s, respectively. And V_K, the design wind velocity at a 100-year design reference period, is 40.16 m/s. So the ratio of $V_{0.05}$ and $V_{0.5}$ to V_K, which can represent ψ_L and ψ_s, respectively, to a certain extent, are

$$r_1 = \left(\frac{V_{0.05}}{V_K}\right)^2 = \left(\frac{32.597}{40.16}\right)^2 = 0.6588 \qquad (10)$$

$$r_2 = \left(\frac{V_{0.5}}{V_K}\right)^2 = \left(\frac{26.223}{40.16}\right)^2 = 0.4264 \qquad (11)$$

It is incontestable to magnify the duration of extreme wind velocities since it is analyzed in months. So $V_{0.05}$ and $V_{0.5}$ must be a bit smaller and so must the values of r_1 and r_2. It is accordingly too conservative to take 0.75 for both ψ_L and ψ_s during the design of foundation structures of sea-crossing bridges on the SLS.

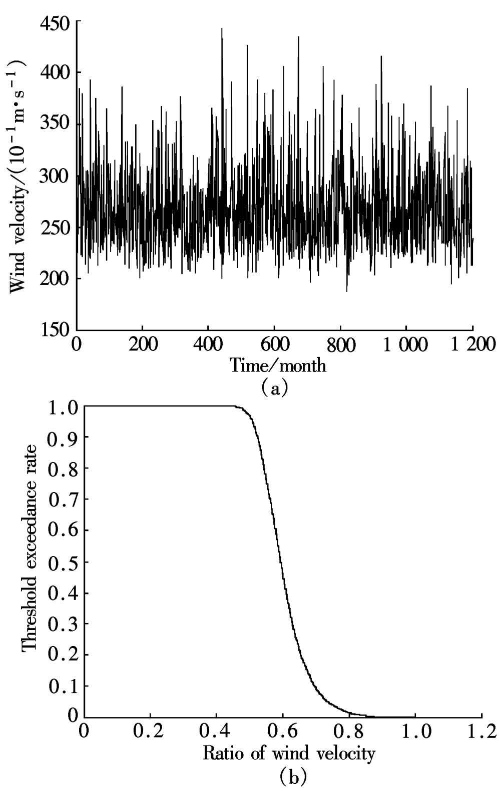

Fig. 1 Simulated monthly extreme wind velocity and statistical analysis of corresponding threshold exceedance rate related to 100-year reference period at the site of the bridge. (a) Simulated monthly extreme wind velocity; (b) Statistical analysis of threshold exceedance rate

2 Target Reliability of Foundation Structures of Sea-Crossing Bridges on the SLS

Selection of β_T, the target reliability index, is a multidisciplinary task. It involves structural analysis, economic analysis, and even the consideration of political decisions[11]. Especially for the design of the foundation structures of sea-crossing bridges on the SLS under the conditions of there being no similar projects till now and there being lack of offshore environmental data, it is more difficult to calibrate a suitable target reliability index. To be simplified, β_T can be determined by comparison with those of other structures. It takes 1.5 as the target reliability index on the irreversible SLS for building structures according to the code GB 50068—2001, and takes 1.0 as the minimum target reliability index for concrete slabs and beams of bridges according to the code GB/T 50283—1999. The JCSS model code, which is the main reliability-based code in different countries, suggests three levels of β_T (see Tab. 3).

Tab. 3 Tentative target reliability indices and associated failure probability related to one-year reference period and irreversible SLS based on the JCSS model code

Relative cost of safety measure	Target index (irreversible SLS)
High	$\beta_T = 1.3$, $P_f \approx 10^{-1}$
Normal	$\beta_T = 1.7$, $P_f \approx 5\times10^{-2}$
Low	$\beta_T = 2.3$, $P_f \approx 10^{-2}$

β_T of foundation structures of sea-crossing bridges on the SLS should be higher than that of common bridges obtained by the current code of highway bridges due to their specialties. Located in complicated and variable ocean environments they are always subjected to enormous environmental loads with high variability, and the ratio of live loads to dead load must have a wide range. Their dominant load is usually a horizontal load combination of wind, wave and current, but not the vehicle load for common bridges. They are also larger in size, and have more degrees of essentiality and risk. Especially, their durability drops more rapidly due to larger degradation and corrosion caused by the action of seawater.

Sea-crossing bridges are always significant to the nation, and the corresponding reliability indices of their concrete components on the crack width of the SLS usually have a wide range[11] and vary in different environments. In order to choose a proper value for different projects, three levels of β_T for foundation structures of sea-crossing bridges on the SLS are suggested, which are 1.5, 2.0 and 2.3, respectively. However, these indices should be checked and evaluated with actual designs in order to illustrate their rationality.

3 Calibration Method for Reliability-Based Factors of Live Loads

3.1 SLS function based on tensile stress of reinforcing bars

It is possible to control the tensile stress of reinforcing bars at the beginning of structural design in order to confine the birth of a concrete crack or its development[12]. According to the relationship between the concrete crack width and the tensile stress of the reinforcing bars, a feasible SLS function based on the contribution ratio of tensile stresses of reinforcing bars produced by various loads to the maximum crack width of concrete can be set up. The concrete crack width with load combinations of short-term effects is defined as

$$W_{s} = K\sigma_{ss} \tag{12}$$

where K is the factor of the concrete crack width that refers to the code JTG D62—2004. The contribution ratio of the load combinations of long-term effects to the concrete crack width is about 1.5 to 1.6 times of that of the load combinations of short-term effects due to shrinkage and creeping of concrete. Here it takes 1.5[13] due to load combinations of long-term effects only occupying a small part of the total load effect. The concrete crack width with load combinations of long-term effects is described as

$$W_{L} = 1.5K\sigma_{sL} \tag{13}$$

Suppose that σ_G and σ_Q are the stresses of reinforcing bars caused by dead loads and live loads, respectively. σ_G is regarded as a long-term load effect, and σ_Q is divided into two parts, σ_{Qs} and σ_{QL}, which represent stresses caused by short-term and long-term effects of live loads, respectively, due to their different contribution ratios to the concrete crack width. So the total concrete crack width is then

$$W = W_{s} + W_{L} = 1.5K\sigma_{G} + 1.0K\sigma_{Q} + 0.5K\sigma_{QL} \tag{14}$$

Expressed in terms of nominal values and partial factors of different loads, it becomes

$$W_{K} = K[1.5\gamma_{G}\sigma_{GK} + \gamma_{Q}\sigma_{QK} + 0.5\gamma_{QL}\sigma_{QL}] \tag{15}$$

Let $[\sigma_{con}]$ be the critical stress of reinforcing bars. The failure probability of the concrete crack width is defined as the probability that the calculated crack width is greater than the critical one.

$$P_{f} = \text{prob}\{K[\sigma_{con}] - W_{K} < 0\} \tag{16}$$

The SLS function can be finally described as

$$g(\sigma) = [\sigma_{con}] - (1.5\sigma_{G} + \sigma_{Q} + 0.5\sigma_{QL}) \tag{17}$$

Since K can be taken completely out of consideration, Eq. (17) only relates to the stresses of reinforcing bars produced by various loads, which are mostly determined by concrete grades, the amount of reinforcing bars, the dimensions of structural components, various loads, and their probability distributions. However, to a certain extent the magnitudes of stresses caused by different loads are proportional for the same component. So their nominal values and variability can be directly substituted by those of different loads.

3.2 Calibration process

The calibration process of the factors of live loads is given in Fig. 2.

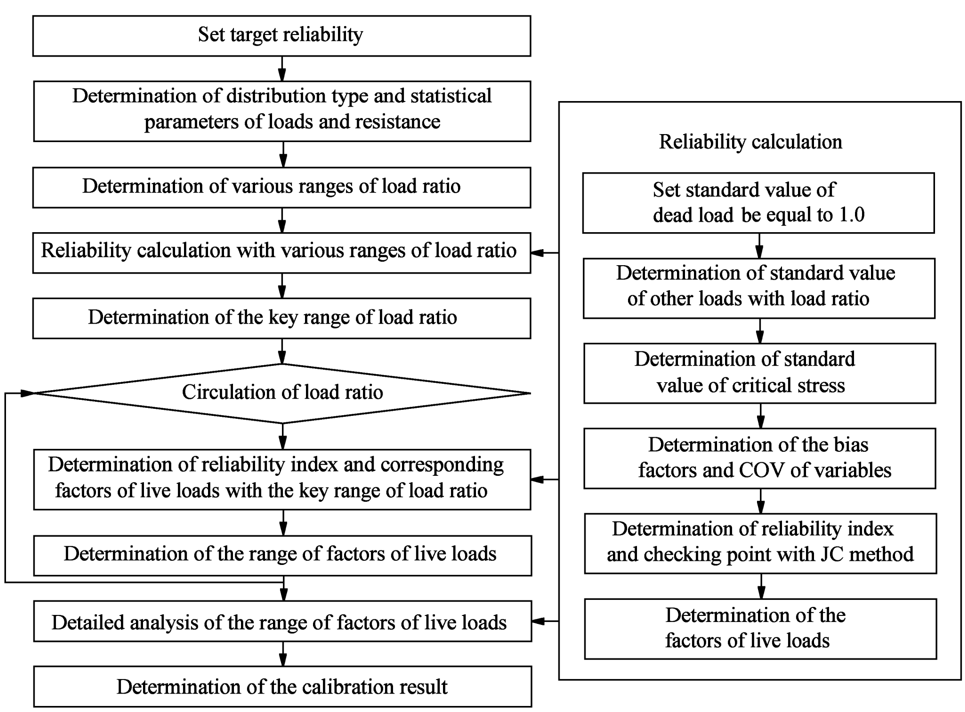

Fig. 2 Flowchart of calibration for factors of live loads

4 Example

This section takes the design of foundation structures of a sea-crossing bridge as an example to further describe this approach.

4.1 Parameters for calibration

There exist all three load cases (see Tab. 4, where D, W, V, V_B, T and W_C represent dead load, wind load, vehicle load, vehicle-brake load, temperature action, wave and current load, respectively) to be calibrated. Here the longitudinal and transverse load cases are regarded as one load cases in terms of their load ratios, which can completely illustrate their differences. Furthermore, the load case of "wind load + wave and current load" is treated as the load case of only "wind load" because they are thought to be perfectly correlated. And the distribution type and the statistical parameter of each load are given in Tab. 5.

Tab. 4 Load cases of calibration

Action direction	No.	Load combination
Longitudinal	1	$D + W$
	2	$D + V + V_B + T + W$
	1	$D + W + W_C$
	3	$D + W + W_C + T$
Transverse	1	$D + W$
	1	$D + W + W_C$

Tab. 5 Distribution types of loads and their statistical parameters

Actions	Distribution type	COV	Bias factors
Dead load	Normal	0.05	0.924 0
Wind load	Gumbel	0.412	0.326 6
Temperature	Gumbel	0.03(max)	0.961 4
Vehicle load	Normal	0.199 4	0.668 4
Vehicle-break load	Gumbel	0.027 9	1.089 9

The specific values of loads and resistance can be taken out of consideration in the reliability calculation since their statistical parameters are proportional to their own nominal values and the nominal value of resistance is a liner function of the nominal values of dead loads and live loads. Therefore, only the ratio of load effects and uncertainties of parameters are needed. In this project, the ratio of load effects ranges from 0.07 to 30.0.

4.2 Calibration result of factors of wind load

Through many times of tentative calculations, the factors of wind load related to the three levels of target reliability proposed are given in Tab. 6, where γ_G represents the partial factor of dead loads. Tab. 7 shows the redesign results of the pile mentioned above with load combination of short-term effects influenced by long-term effects on the concrete crack width of the SLS using the factors in Tab. 6.

Tab. 6 Factors of wind load for a sea-crossing bridge

β_T	P_f	γ_G	ψ_s	ψ_L
1.5	7×10^{-2}	1.0	0.55	0.35
2.0	3×10^{-2}	1.0	0.65	0.35
2.3	1×10^{-2}	1.0	0.70	0.40

Tab. 7 Redesign results of the pile mentioned above

β_T	Diameter	Quantity
1.5	40	106
2.0	40	120
2.3	40	131

The amount of reinforcing bars needed at $\beta_T = 1.5$ is close to that according to the code JTJ 023—85, and the amounts needed at $\beta_T = 2.0$ and $\beta_T = 2.3$ rationally range between those according to the codes JTJ 023—85 and JTG D62—2004. Finally $\beta_T = 2.3$ is chosen in the project, and is proved to be acceptable.

5 Conclusion

In order to make a better design for foundation structures of sea-crossing bridges on the SLS, three levels of target reliability based on the JCSS mode code and the characteristics of those structures are proposed. And a new approach of calibrating the factors of live loads based on the contribution ratio of tensile stresses of reinforcing bars produced by various loads on concrete crack width is also established. This approach can increase the efficiency of calculation by reducing the amount of parameters needed and load cases in the calibration. Finally they are both proved to be reliable by an actual design.

However, the reliability-based factors of wind load in that example are a bit conservative because actually "wind load" and "wave and current load" are not perfectly correlated. Moreover, in order to obtain calculation results more precisely, the combination theory of wind, wave and current load should be deeply studied and the environmental information of the sea area should be further investigated. In addition, the same calibrations of other sea areas should be carried out in order to provide more sufficient references for the field of structural design in the current code of highway bridges.

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跨海桥梁基础结构正常使用极限状态的设计方法

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摘要:由于跨海桥梁的环境效应有别于一般桥梁,正常使用极限状态所对应的目标可靠度也必然不同,因此,基于 JCSS 模式规范建议了目标可靠度指标分别为 1.5,2.0 和 2.3 的跨海桥梁基础结构正常使用极限状态三级可靠度水平,并提出了一种可变荷载系数的标定新方法,即通过各类荷载引起的钢筋拉应力对于混凝土裂缝宽度的贡献率不同建立基于钢筋拉应力的正常使用极限状态方程.最后,依据可靠度计算的校准法,结合具体工程进行了基于目标可靠度的可变荷载频遇值系数和准永久值系数的标定,通过设计实践证明所建议的目标可靠度指标值是合理的,采用的标定新方法是可行的.

关键词:跨海桥梁;目标可靠度;校准法;频遇值;准永久值;基础结构

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