Design Method for Bottom Single Blade Steel Rotation Pile Foundation: Case Study in Vietnam

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ABSTRACT: Bottom single blade Steel Rotation Pile (SRP) is a large diameter steel pipe pile with a helical blade welded to the edge with a lot of advantages such as rapid construction, small construction area, especially less vibration, less noise, environment friendly and high resistance which has been applied recently in the urban of Vietnam. However, how to design SRP foundation in ensuring the conformity with the specification for bridge design in Vietnam is an important question and the new Design Specification for SRP has been edited. This article presents the way to find out the method to design SRP foundation in Vietnam as a case study.

Keywords: Steel Rotation Pile, bridge foundation, design method in Vietnam.

1. INTRODUCTION

Steel Rotation Pile (SRP) is a large diameter steel pipe pile with a helical blade welded to the edge. During construction, with a casing rotator for example, the pile is rotated in pressing and the blade on the edge performs the digging that drives the pile into the ground as a screw. Since the 1990s, this kind of foundation has been applied successfully for many bridges in Japan and in the other countries, especially in urban area based on the big advantages, such as rapid construction, small construction area, especially less vibration, less noise, environment friendly and high resistance.

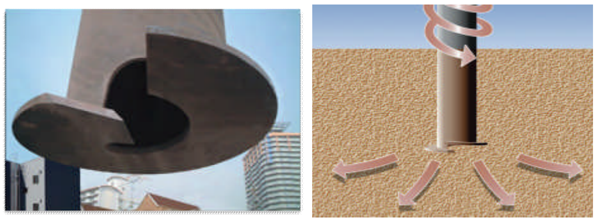


Figure 1 Steel rotation pile

Recently in Vietnam, this new kind of the foundation was applied for Hoang Minh Giam flyover and will be used for Ring Road No.3 part Mai Dich - Thang Long of Hanoi (Figure 2).

Figure 2 Hoang Minh Giam flyover and Ring Road No.3

In Vietnam, bridge foundation is now designed based on Load and Resistance Factors Design (LRFD) method [1, 16, 17, 18] with the Specification for bridge design 22TCN 272-05 in section 10 [1] but this section shall apply only for the design of spread footings, driven piles and bored piles foundations.

In the world, SRP design is mentioned in some specifications [7, 10, 15] such as JRA 2012 of Japan which uses Allowable Stress Design (ASD) method. However as mention below, ASD method cannot be used for bridge design in Vietnam.

Therefore, the new LRFD method for SRP foundation design is required to be established [19], the key content will be discussed in this paper: load factors, new resistance factors, new bearing formula.

2. LRFD DESIGN METHOD

2.1 ASD and LRFD methods

The design of the foundations has been traditionally based on ASD method, safety is achieved in the foundation element by restricting the estimated loads (or stresses) to values less than the ultimate resistance divided by a safety factor (SF). In ASD all of these loads are assumed to have the same variability. As a result, load factors are not applied on the load combinations considered for either the strength or service limit states. The factor of safety is a number greater than unity. The SF provides reserve strength in the event that an unusually high load occurs or in the event that the resistance is less than expected. For the Service Limit State, unfactored loads are used to calculate deformations, and these deformations are compared to the maximum tolerable values.

ASD method has many limitations: does not adequately account for variability of loads and resistances, the SF is applied only to resistance; selection of a SF is subjective, and does not provide a measure of reliability in terms of probability of failure, etc.

To overcome these deficiencies, LRFD method [1, 2, 6] was developed from the 1950. The idea is that:

$$\text{Resistance} \geq \text{Effect of Loads}$$

And the resistance side is multiplied by a statistically-based resistance factor, f (value is usually less than one), the load components on the right side are multiplied by their respective statistically based load factors, γ_i, (values are usually greater than one).

The process of assigning values to resistance factors and load factors is called calibration. A design code may be calibrated by using:(1) judgment, (2) fitting to other codes, (3) reliability theory, or (4) a combination of approaches.

Calibration by judgment requires experience and the fundamental disadvantage of this method of calibration is that it results in non-uniform levels of conservatism. Calibration by fitting to other codes such as ASD can be used where there is insufficient statistical data to perform a more formal process of calibration by reliability theory. This method was used for AASHTO LRFD old version before 1998 and for example, gave the values of resistance factors from 0.7 to 0.56 fitting to the SF from 2 to 2.5. However, the research [6, 11] so that LRFD factors converted from SF of ASD did not provide the desired level of reliability and NCHRP of U.S recommend to use reliability theory for (applied for AASHTO LRFD new version from 1998 until now).
Therefore, for the assignment of load and resistance factors in SRP design, the calibration by reliability method should be selected.

2.2 Basic equation of LRFD method

In the bridge design specification [1, 2], the basic equation is:

$$\sum \eta_i \gamma_i Q_i \le \varphi R_n = R_r \qquad (1)$$

in which:

γ_i = load factor: a statistically based multiplier applied to force effects

ϕ = resistance factor: a statistically based multiplier applied to nominal resistance

η_i = load modifier: a factor relating to ductility, redundancy and operational importance [1]

Q_i = force effect

R_n = nominal resistance

R_r = factored resistance: φR_n

3. DESIGN METHOD FOR SRP

3.1 Experimental and geological data

For calibration of SRP design factors by reliability method, loading test data shall be collected [7, 9, 12, 15, 16] There are many reliable data of SRP loading test in Japan and one data in Vietnam (Hoang Minh Giam flyover). However, a few loading test data of SRP can be found in the other countries. Variety of data of SRP loading test data are shown in Table 1:

Table 1 Editorial Instructions

Item	SRP foundation
Number of data:	23 reports
- Pile tip resistance	22
- Shaft resistance (sand, gravel)	37
- Shaft resistance (clay, sand-clay)	21
Pile diameter Dp (mm)	318～1600
Blade diameter Dw (mm)	1.5 Dp, 2 Dp
Depth L (m)	12.5～55.7
Below soil layers	All Soil
Bearing soil layer	Sand, gravel

Some typical data are shown in Table 2:

Table 2 Editorial Instructions

No	Dp	Dw	L	Bearing layer	Pile tip R	Shaft R
	(mm)	(mm)	(m)	(type)	(kN)	(kN)
1	406.4	812	34.5	gravel	1978	1463
2	800	1200	15.7	sand	7620	1299
3	900	1350	55.2	gravel	6250	6599
4	1000	1500	25.1	sand	11009	3478
5	1600	2400	51.0	altered rock	43330	13242

Almost data were collected in Japan, so we should do some comparison of the soil conditions in Japan, Vietnam and other countries [2, 4, 5, 8, 13, 15, 18].

In Vietnam, the soil type and depth of bearing layer are different between the North and South. In Japan, the scope of the soil bearing layer are also varied.

For example, the data of boring holes in the North of Vietnam shows bearing layer is not so deep (from about 30-50m), as same as in the Western Chugoku region of Japan. Besides, geology conditions in the South of Vietnam is quite similar to the Tokyo Bay area, the coastal part of Japan, with the surface layer is soft soil, very soft clay and very deep bearing layer (Figure 3).

In the US, the typical geological bearing soils are mainly sand and gravel. However, relatively depths are not so big, mainly under 20m. In Europe, the bearing layer is mainly rocky and small depths, mainly less than 20m.

So in general, the geological conditions of Japan are rather similar to the geology of Vietnam when comparing to the US and Europe conditions. Then the loading test data in Japan are quite useful for calibration of SRP design factors.

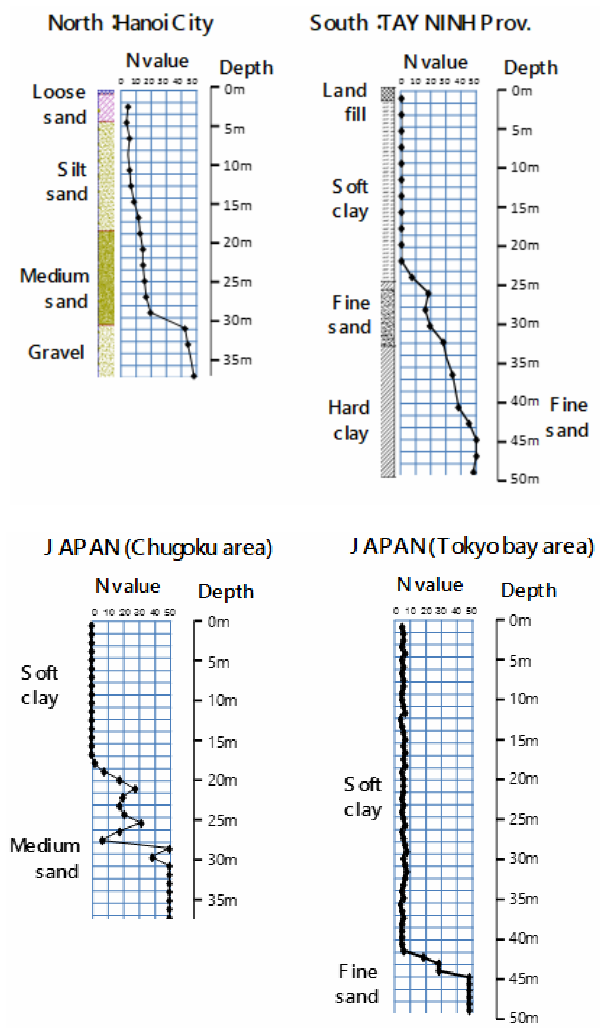


Figure 3 Boring hole examples in Vietnam and Japan

3.2 Loads and load combinations for SRP design

The loads for SRP design, of course, shall follow the design of bridge superstructure as specified in the bridge specification [1, 2, 18]. So it doesn't need to mention more detail about the permanent and transient loads in this paper.

For the load factors, LRFD method applies the factors for various permanent and transient load types using the equation (1). Selection of the load factor(s) to be used is a function of the type of load and limit state being evaluated (a limit state is a condition beyond which a foundation or structure component ceases to fulfil its intended function).

The load factor, γ_i, chosen for a particular load type must consider the uncertainties in the: magnitude and direction of loads, location of application of loads and possible combinations of loads. To fulfil with the design of bridge superstructure, abutment and pier, the load factors and load modifier for SRP design should be taken the same values with the above structures: The permanent and transient loads and forces shall be also considered following the bridge design specification [1, 2]. The SRP foundation should be optimal designed to support these loads.

In conclusion, the load factors, load modifier as well as load combinations for SRP design in Vietnam shall be selected as specified in the bridge design specification 22TCN 272-05.

3.3 New Resistance factors for SRP design

Resistance factors for SRP are not mentioned in the 22TCN 272-05 so need to be assigned by calibration of reliability method based on experimental data [2, 5, 6].

The resistance factor of the foundation can be obtained from formula (2) [5, 6, 8, 11]:

$$\varphi = \frac{\lambda_R\left(\frac{\gamma_D Q_D}{Q_L}+\gamma_L\right)\sqrt{\left[\frac{\left(1+COV_{Q_D}^2+COV_{Q_L}^2\right)}{\left(1+COV_R^2\right)}\right]}}{\left(\frac{\lambda_{Q_D} Q_D}{Q_L}+\lambda_{Q_L}\right)\exp\left\{\beta_T\sqrt{\ln\left[\left(1+COV_R^2\right)\left(1+COV_{Q_D}^2+COV_{Q_L}^2\right)\right]}\right\}} \qquad (2)$$

in which:

φ = resistance factor ; λ_R = resistance bias factor

COV_Q = coefficient of variation (the ratio of the standard deviation to the mean) of load ; COV_R = coefficient of variation of resistance; β_T = target reliability index.

γ_D, γ_L = dead and live load factor ; Q_D / Q_L = dead to live load ratio; $\lambda_{QD}, \lambda_{QL}$ = dead and live load bias factor

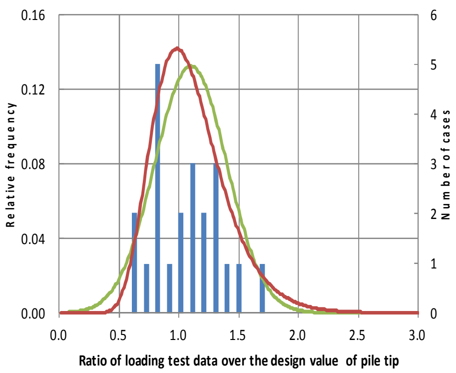
There is relationship between reliability index β_T and probability of failure P_f [3]. β_T of SPT method was calculated and was found to be between about 1.5 and 3.0 [5, 11]. A reasonable value of target reliability index, β_T, for single piles appears to be in the range of 2.0 to 2.5, corresponding to P_f between 10^{-1} and 10^{-2}.

Then a reduction factor RD can be calculated by the index from the confidence interval. This index is divided the lower limit of the confidence interval by the average value, and the reduction factor is the ratio of the index for in case of actual number of data and enough data. Confidence interval is calculated following equation:

$$CI = \mu \pm t(1.0, n-1) \times \sigma / \sqrt{n} \qquad (3)$$

Equation (3) is for a confidence interval of 95% one-sided, using the ratio of the lower limit of the reliability interval for sufficient data as reduction factor.

Each resistance factor is re-calculated by SRP loading data following LRFD methods. About shaft friction, each data of sand and clay is evaluated individually. Shaft resistance is measured by stress of pile for each layer, so it is able to get some data by one loading test (Figure 4).



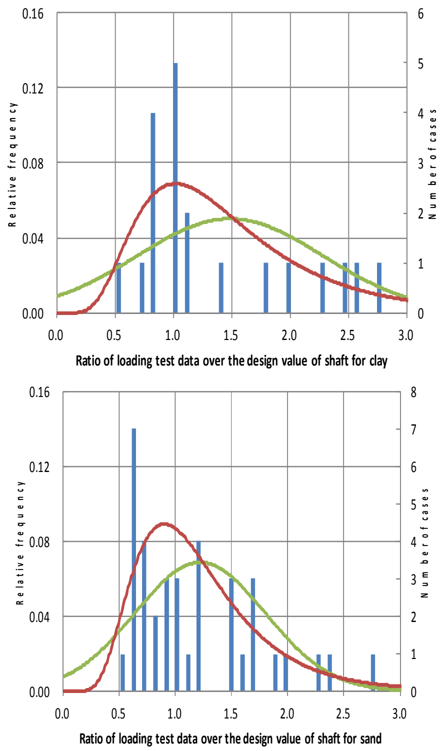


Figure 4 Data analysis for pile resistance

Using the formula (2) and the defined method in the items 2.1 and 3.3, the main results are shown in Figure 4 for pile tip resistance and pile shaft resistance.

The values of resistance factor corresponding to target reliability index, β_T are calculated as in Table 3. Here the value at β_T = 2.33 will be chosen for the next step.

Table 3 Editorial Instructions

Content	**Resistance factor φ**			**Number of data n**
β_T	2.00	2.33	3.0	812
Pile tip resistance	0.70	0.62	0.49	1200
Shaft resistance (sand, gravel)	0.53	0.45	0.32	1350
Shaft resistance (clay, mixed clay)	0.58	0.48	0.33	1500

The values of reduction factor with the number of data defined in Table 3, are shown in the Table 4 as follows:

Table 4. Reduction factor

Resistance	**Mean μ**	**Standard deviation σ**	**RD (lower CI)**
Pile tip resistance	1.10	0.30	0.99
Shaft resistance (sand, gravel)	1.22	0.57	1.00
Shaft resistance (clay, mixed clay)	1.48	0.79	0.96

Finally, the recommendation resistance factor is shown in Table 5. This value is obtained by multiplying calculated resistance factor and reduction factor.

Table 5. Recommendation resistance factor

Resistance	φ × RD		Recommendation resistance factor)
Pile tip resistance	0.61	⇒	0.60
Shaft resistance (sand, gravel)	0.45	⇒	0.45
Shaft resistance (clay, mixed clay)	0.46	⇒	0.45

The uplift resistance factor can be also assigned by the same method based on experimental data.

Finally, resistance factors for SRP at the strength limit state [19] for static analysis shall be taken as specified in Tables 6, unless regionally specific values are available.

Table 6. Resistance factors for SRP (single pile)

Condition		Resistance factor
Nominal Resistance in Axial Compression, φ_{st}	Pile shaft resistance: all soil and gravel	0.45
	Pile tip resistance: sand and gravel	0.60
Uplift Resistance, φ_{upst}	Pile shaft resistance: all soil and gravel	0.45
	Pile tip resistance: sand and gravel	0.60

3.4. Bearing capacity of SRP

3.4.1. Determination of new formula for bearing capacity

The bearing capacity of a pile is determined as follows: the pile must sustain with sufficient certainty loadings in different loading cases after driving, and settlements and horizontal movements must be within the permissible structural tolerances.

The bearing capacity of the pile is determined either based on the structural or geotechnical bearing capacity, and the smaller one is chosen to the design capacity.

The structural bearing capacity of the pile is determined by the strength of the pile structure. The structural bearing capacity is checked for the axial loads, bending moments from the horizontal loads, eccentricities loads. In addition to the requirements of the supported structure the bearing capacity of the pile should be considered for buckling, additional loads, such as negative shaft friction and bending of the inclined piles due to the ground settlements or bending caused by one-sided soil pressure or lateral resistance. In a completed structure the steel pipe pile is usually filled with soil. The structural capacity of the pile is formed by the bearing capacity of the steel pipe considering the corrosion reduction. Permitted material stresses of the pile are determined on the basis of the pile material and soil conditions. In bouldery soil conditions it may be appropriate to reduce the material stresses permitted in normal situations. The recommended minimum thickness of the steel pipe pile driven from the upper head is 9mm [18, 19]. The corrosion of the pile should be considered when determining the long-term structural bearing capacity of the pile.

So for SRP foundation, the material resistance shall comply with steel pile structure calculation by the current bridge specification [1, 18, 19]. In addition, this resistance in most cases is usually greater than geotechnical resistance so in this paper, we pay more attention in the geotechnical bearing capacity.

The geotechnical bearing capacity is determined according to the ground conditions, construction and checking procedures.

The geotechnical bearing capacity of the pile consists of the bearing capacity of the pile tip resistance, and of the bearing capacity of the pile shaft resistance. The mobilization of the tip resistance requires a considerably larger settlement than the mobilization of the shaft resistance. The effects of the negative shaft friction on the geotechnical bearing capacity are checked separately, when negative shaft friction is developed or the pile is plugged. The possible corrosion of the pile does not lower the geotechnical bearing capacity.

This instruction is mainly concerned with SRP, the geotechnical bearing capacity of the pile can be determined in many different ways which can be roughly divided into direct and indirect methods.

Indirect methods include:

- Static bearing capacity formulas
- Empiric methods based on the penetration resistance
- Stress wave analysis without stress wave measurements.

Direct methods include:

- Dynamic test loadings
- Static test loadings.

In design stage the indirect methods are used in designing of the pile dimension, penetration depth and the construction equipment. These are checked on the site using direct methods, usually with dynamic test loadings.

The bearing capacity of the SRP consists of the pile tip resistance and external shaft resistance.

2.1.4 Geotechnical bearing capacity formula

The studies in Japan [9, 12, 13, 14] and item 3.1 have shown the sufficient data and scientific basis for determining the bearing capacity of Bottom single blade Steel Rotation Pile which is also specified in the specification JRA 2012 [10].

The other studies such as in US, Euro and Australia [3, 4, 8, 15] are mainly for small diameter or multi-blades rotation (screw) piles almost used for buildings, not for bridges. However, these studies also show the main role of screw blade (rotation wing) in the resistance components of the rotation steel pile.

Consequently, in combination with the geological analysis in item 3.1, the using a part of the bearing capacity formula of JRA 2012 to determine the bearing resistance formula of SRP for LRFD design is acceptable with the above scientific basic.

The geotechnical bearing resistance formula for SRP is following:

$$R_R=\varphi R_n= \varphi_{pst}R_p+\varphi_{sst}R_s \quad (4)$$

in which:

φ_{pst} = Resistance factor of pile tip for SRP, static analysis
φ_{sst} = Resistance factor of shaft for SRP, static analysis
R_p = Pile tip resistance (kN)
R_s = Pile shaft resistance (kN)

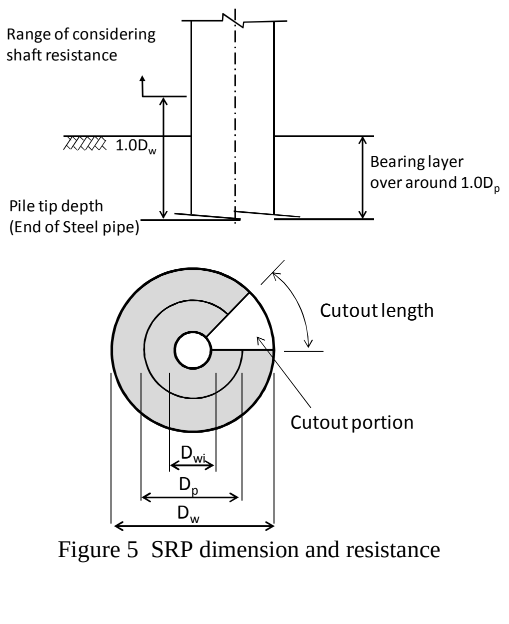


Figure 5 SRP dimension and resistance

The pile resistance can be referred from the bearing capacity formula of JRA 2012.

The pile shaft resistance can be determined by:

$$R_s = q_s A_s \quad (5)$$

Where:

R_s : Pile shaft resistance (kN)
qs : unit shaft resistance of pile (kN/m2)
As : Area of pile shaft surface $= \pi D_p L$ (m^2)
Dp: Pile diameter (m),
L: Length of the section to take into account the shaft resistance of the pile upper 1Dw from pile tip (m), (m2)

The nominal unit shaft resistance of SRP, in kN/m2, shall be taken as:

For non-cohesion soils

$$q_s = 3N \text{ (Maximum 150)} \quad (6)$$

For cohesive soils

$$q_s = c \text{ or } 10N \text{ (Maximum 100)} \quad (7)$$

Where:

N: SPT blow count, uncorrected for overburden pressure
c : cohesion (kN/m^2)

The pile tip resistance can be determined by:

$$R_p = q_p A_p \quad (8)$$

Where:

Rp : Pile tip resistance (kN)
q_p : Unit tip resistance of pile (kN/m^2)
Ap : Area of pile tip = $\pi D_w^2/4$
Dw: Blade diameter (m)

The nominal unit tip resistance of SRP in bearing layer, in kN/m2, shall be taken as:

For bearing layer of sand

qp = 120N (Maximum 6,000, Dw is 1.5Dp) (9a)

qp = 100N (Maximum 5,000, Dw is 2.0Dp) (10a)

For bearing layer of gravel

q_p = 130N (Maximum 6,500, D_w is 1.5D_p) (9b)

qp = 115N (Maximum 5,750, Dw is 2.0Dp) (10b)

N: SPT blow count at bearing layer, uncorrected value

Pile construction shall be finished on full examination of the finishing conditions so as to ensure the bearing capacity. The finishing conditions should be determined based on results of test piling operation, and are represented by such factors as embedded depth of the pile, dynamic bearing capacity. Embedded depth of a pile specified in design documents or confirmed by results of trial piling test.

For the uplift resistance of SRP, it should be estimated in a similar manner to determinate the shaft resistance as specified above, and it can be assumed that the steel blade behaves like an anchor as shown Figure 6.

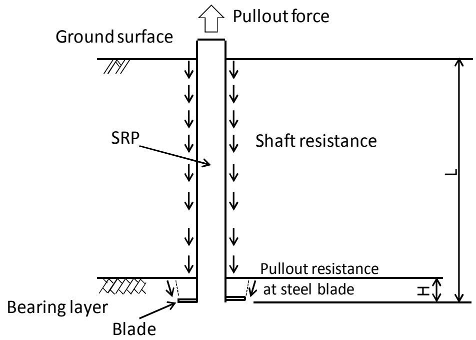


Figure 6 Uplift of SRP shaft and steel blade

3. CONCLUSION

SRP foundation for bridge is suitable for transport works especially in urban area with the key advantages: easy application in narrow space, fast construction, reduce vibration and noise, high quality control, small influence to nearby monument, environmentally friendly, recyclable, etc. The efficacy is shown in many reel projects including two overpass projects in the capital of Vietnam.

For application of SRP foundation, the specifications for design, construction and acceptance are required. To fulfil with the LRFD design of bridge superstructure, abutment and pier, the load factors, load modifier as well as load combinations for SRP design shall be selected as specified in the specification 22TCN 272-05. The resistance factor values for SRP can be assigned based on loading test data according to LRFD method, in compatibility with the bridge design specification system in Vietnam. The normal resistance for geotechnical bearing capacity can be referred from the formula in JRA 2012 with the carefully study. These above things are the most important contents of the new LRFD specification for SRP design (TCVN 11520:2016) in the study case of Vietnam.

The Vietnamese case studies show that the new method based on LRFD can be established and used effectively for SRP foundation design instead of ASD method of Japan if need.

The uplift resistance, settlement and other checking for SRP foundation LRFD method design as well as SRP design examples for calibration between the different specifications, the construction requirements and technologies will be discussed in the next papers.

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