THE EFFECT OF SUCTION ON THE FOUNDATIONS OF SUPER LONG SPAN BRIDGES DURING AN EARTHQUAKE

FUKUI Jiro*, ISHIDA Masahiro**, ASAI Ryuichi***

1. Introduction

A rarional design of deep-water foundations is one of the technological issues in the construction of super long span bridges. Although many deep-water foundations have been constructed, it is anticipated that future constructions will be required to deal with even at the seabed and construction conditions. The development is also greatly anticipating technological advances that will facilitate the installation of rationally designed foundations under such severe conditions and at lower cost.

This report contributes to the development of more rational design methods for the deep-water foundations of super long span bridges, focusing on the effects of suction on the foundations. Suction here refers to the apparent resistance of the substructure to overturn due to inertia or other factors during an earthquake, as well as that related to water pressure differentials acting on the bottom surface during uplift and rotation of an underwater foundation. The resistance is manifested as a downward force on one side of the footing, corresponding to the magnitude of the differential water pressure.

Fig.1 shows a schematic view of the design approach when suction is considered. Uplift of the footings of super long span bridges is considered in the conventional design method, but the design method for spread footings described in the current specifications for highway bridges in Japan1) takes no account of any effect of suction at the underside of the footing during uplift. Since this suction acts vertically, it adds to the effect of the moment and vertical forces resisting rotation. If this total effect is considered during design, it will be seen that the foundation dimensions can be somewhat economized from those recommended by the conventional design method. In addition, identifying the characteristics of the suction forces may well allow development of new foundation structures that make more efficient use of the suction mechanisms to resist uplift.

This report describes laboratory experiments carried out to observe the characteristics of the suction forces. And an economized design approach is suggested on the basis of these results.

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* Team Leader,Foundation Engineering Research Team, Public Works Research Institute
** Senior Researcher,Foundation Engineering Research Team, Public Works Research Institute
*** Visiting Researcher,Foundation Engineering Research Team,Public Works Research Institute

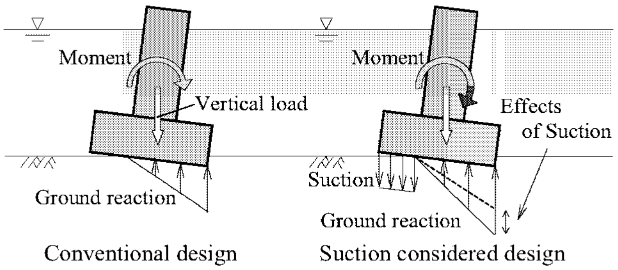

Fig.1 The design approach

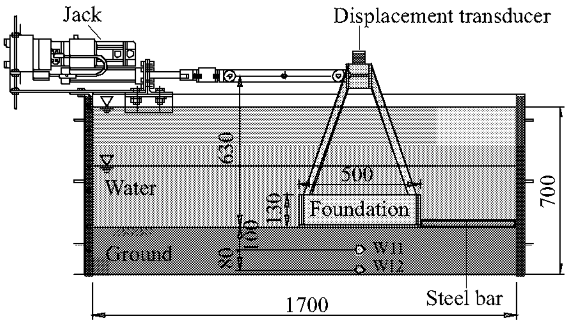

Fig.2 Experimental Models

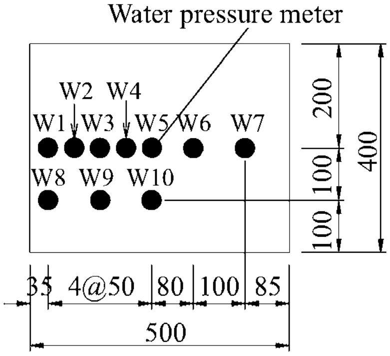

Fig.3 Water pressure meter location (Foundation bottom)

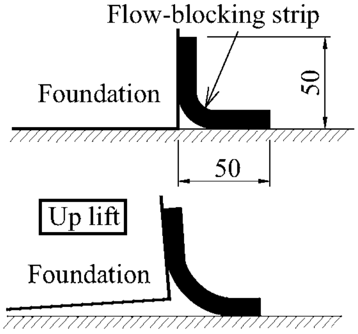

Fig.4 Flow-blocking strip

2. Experimental Models and Method

Fig.2 shows a schematic of the laboratory apparatus. The water tank measured 1700 mm long × 800 mm wide × 700 mm high. After the ground model was installed, the tank was filled with water and the foundation model was constructed.

Two ground models were considered; an impermeable model (hardness-40 rubber, 23 mm thick, glued to concrete blocks on the tank bottom) and a permeable model (Kashima sand, 200 mm thick, relative density 70%, permeability 0.061 cm/s).

The foundation model consisted of a footing formed by filling a 500 mm long × 400 mm wide × 130 mm thick steel mold with concrete and a frame of ϕ 34 mm steel pipes. The model was loaded at the top of the frame in the horizontal direction using a jack under displacement control. Measurements were conducted of applied load (horizontal), displacement and rotation angle at both loading points, and water pressure at 10 points on the bottom face of the footing (see **Fig.3**). The water pressure was also measured at 2 points within the sand in the permeable ground model.

To focus on the characteristics of resistance to uplift, horizontal sliding under horizontal load was prevented by fixing the model with a steel bar. The experimental cases are listed in **Table 1**. Parameters of ground type, base rotation speed, depth of water over the foundation, and the presence of structure to block inflow at the underside of the foundation were considered. The flow-blocking strip listed in **Table 1** was a rubber strip placed along the bottom edge of the footing (**Fig.4**) to impede the ingress of water into the space on the underside of the footing after the foundation began to lift.

Table 1 The experimental cases

Case	Ground type	Rotation speed	Bottom flow	Depth
C11	impermeable	0.2 rad/sec	non-blocking	250mm
C15		0.05 rad/sec		500mm
C16		0.1 rad/sec		
C17		0.2 rad/sec		
C25	permeable	0.2 rad/sec		
C35	impermeable	0.05 rad/sec	blocking	
C36		0.2 rad/sec		

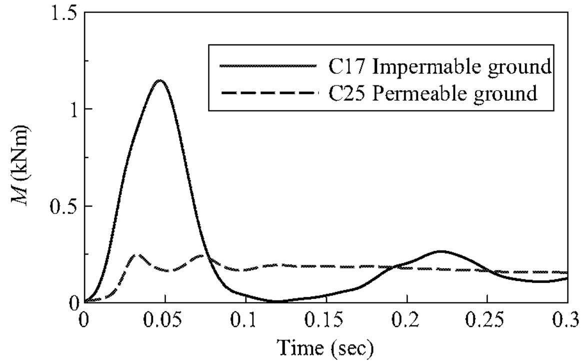

Fig.5 Time history of the resistance moment over impermeable and permeable ground

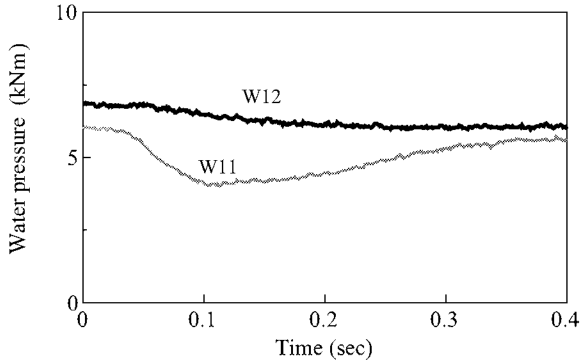

Fig.6 The time series of water pressure within the permeable ground

3. Experimental Results

(1) Suction forces on different ground types

Fig.5 shows a time history of the resistance moment over impermeable and permeable ground. These results show that the resistance moment (horizontal force multiplied by height of 630 mm above footing underside) was lower above permeable ground than above impermeable ground. The time series of water pressure (all values relative to atmospheric pressure) within the permeable ground is shown in **Fig.6**. The resistance moment varied with pore water pressure in the sand. That is, it is clear that while water was only able to enter the space between the lifting foundation at the edge of the foundation and impermeable ground, it was also able to enter this space in an upward permeation flow from the bottom itself when the ground was space at the edge. This prevents suction from acting effectively and reduces the resistance moment, when the ground is permeable. Thus, when the bottom is permeable, it is necessary to make a thorough investigation of soil parameters such as permeability during boiling.

(2) Relationship between angular speed of foundation and rotational resistance

Fig.7 presents the time history of the resistance moment for cases C15-C17, which involved different angular speeds over impermeable bottom. The angular speed shown here was calculated using the horizontal displacement of the two locations at the top of the flame. The peak resistance moment of the foundation increased with the angular speed. **Fig.8** provides the time history of the pressure indicated by meter W2 (85 mm from the lifting edge of the footing) for the same cases. The negative pressure increased with the angular speed. That is, the higher the angular speed, the greater the suction that occurred, which is expected to increase the resistance

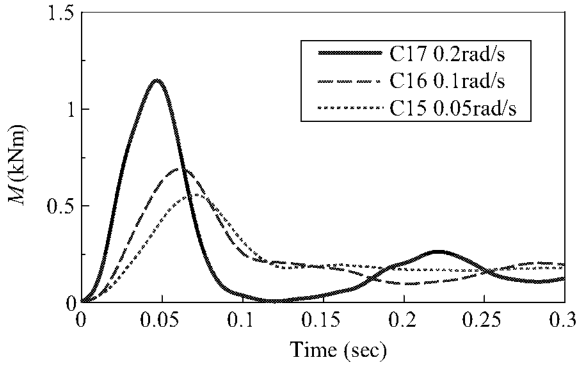

Fig.7 The time history of the resistance moment for cases C15-C17

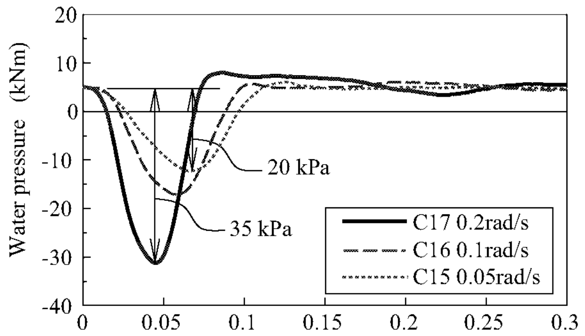

Fig.8 The time history of the pressure indicated by meter W2

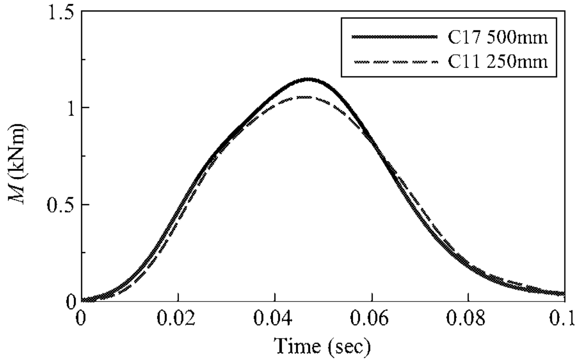

Fig.9 The time histories of the resistance moment for cases C11 and C17

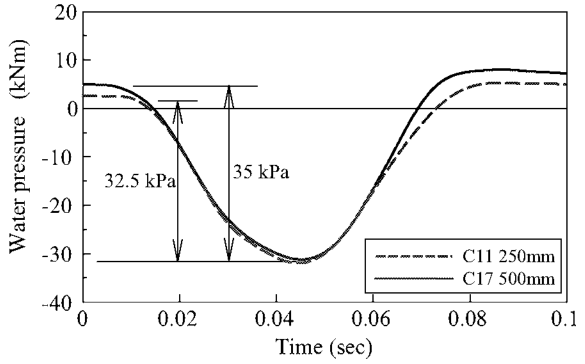

Fig.10 The time history of water pressure for cases C11 and C17(at meter W2)

moment. In these tests, however, the observed suction (pressure differential) was around 20-35 kPa lower than the vacuum condition (reduction in pressure corresponding to static water pressure + atmospheric pressure). The suction was also observed to dissipate quickly.

(3) Effect of water depth on resistance to rotation

Fig.9 shows the time histories of the resistance moment for cases C11 and C17, in which the water depths were different. The peak resistance moment was higher in C17, in which the water was deeper.

The time history of the water pressure observed at meter W2 (**Fig.10**) reveals that there was some pressure difference due to the difference in water depths, although the differential between the maximum negative pressures corresponded quite closely to the pressure differential due to the depth difference. Thus, it seems likely that the greater the depth, the greater the suction, and the greater the resulting peak resistance moment.

(4) Effect of flow blocking strips on rotational resistance

Fig.11 shows the time history of the resistance moment observed in cases C35 and C36, when the flow blocking strips were installed along the bottom lifting edge of the footing. These moments were considerably higher than in the corresponding cases without the flow blocking strips (**Fig.7**). These results also indicate that the peak resistance moment was independent of angular speed.

Fig.12 shows the time history of water pressure at the underside of the foundation. This pressure approached nearly the vacuum condition, and this condition was maintained after the peak. Since the structure used for this experiment did not perfectly block water ingress, however, the resistance moment gradually fell (**Fig.11**) after peaking. The abrupt decrease in resistance moment in test C36 at around t = 1.2 s was due to the collapse

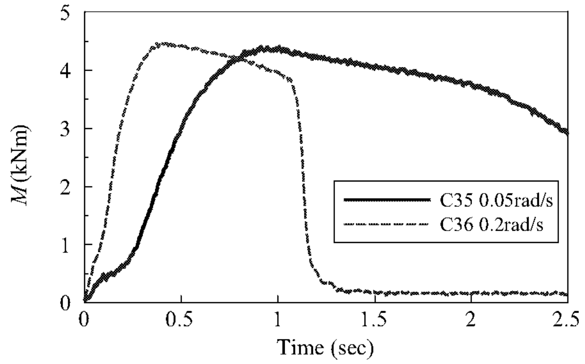

Fig.11 The time histories of the resistance moment for cases C35 and C36

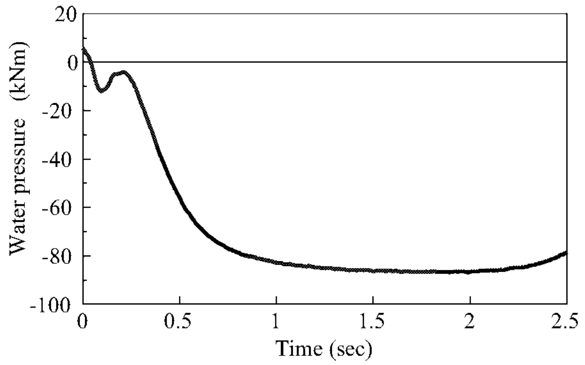

Fig.12 The time history of water pressure for cases C35 (at meter W2)

of the strip under the foundation, allowing water ingress.

4. Sesmic Desige Method with consideration of Suction

(1) Action of suction

The results of the tests with the laboratory model can be divided into two broad categories.

a) When suction magnitude is dependent on angular speed;

The space below the lifted foundation fills with water and the waterflow volume and negative pressures correspond to angular speed (Condition A).

b) When suction magnitude is independent of angular speed;

Water is slow to flow into the space below the foundation when it is lifted, or is blocked by structure, such that a vacuum develops below the foundation. Pressure fluctuations subsequently stop and a certain level of suction is maintained (Condition B).

In the design of foundations, the structure is determined by the magnitude of the forces (accelerations) or displacements. During foundation rotation under Condition A, the angular speed is nearly zero as the moment acting on it or the rotation angle reaches a maximum. Accordingly, almost no suction develops under Condition A, and as such this condition has no effect on the design of the foundation. Under Condition B, however, since the suction is maintained independent of the foundation angular speed, suction influences on design of the foundation. The next section is an investigation of Condition B, focusing on the case when water enters below the foundation edge above impermeable ground.

(2) Expression for resistance to uplift including the effect of suction

The equation for uplift of a spread footing given in the current The specifications for highway bridges in Japan1)(reffered to as original equation) is expanded here to account for the effect of suction. The expanded version is referred to as the corrected equation.

As shown in **Fig.13**, the ground reaction and the suction counteract the overturning moment acting on the underwater foundation. Accordingly, the resistance moment M represents the sum of the moment M_E due to the ground reaction and the moment exerted by suction M_S, as given by eq(1).

$$M = M_E + M_S \tag{1}$$

M_E bears a non-linear relation with rotation angle θ, as expressed by eq(2) , eq(3)2). Where the fluctuations

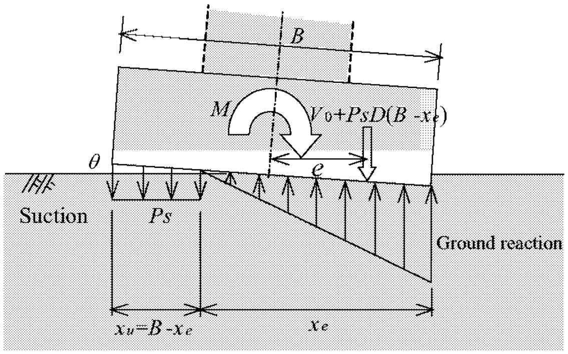

Fig.13 The ground reaction and the suction counteract

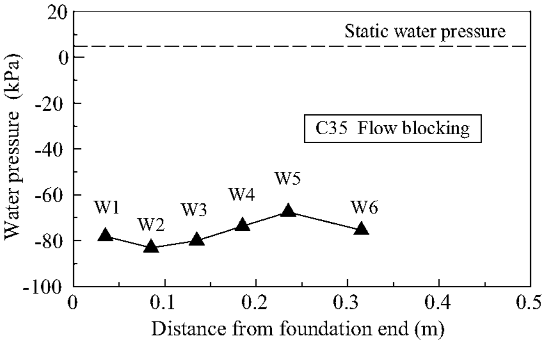

Fig.14 The water pressure distribution on the bottom

of the vertical force due to suction are considered. Since the suction acting on the foundation in this case is the fluctuation of pressure if the static water pressure and atmospheric pressure are both set to zero, an isobaric condition may be assumed. This is also shown in the experiment. The water pressure presented in **Fig.14** for case C35, measured on the underside of the foundation during uplift, showed an isobaric distribution and nearly vacuum condition.

$$\frac{M_E}{M_0} = 3\frac{e}{B}\left(2 + \frac{BDp_s}{V_0}\left(6\frac{e}{B} - 1\right)\right) \tag{2}$$

$$\frac{e}{B} = \frac{1}{2} + \frac{BDp_s/V_0}{6\left(\theta/\theta_0\right)} - \frac{\sqrt{\left(BDp_s/V_0\right)^2 + 4\left(BDp_s/V_0 + 1\right)\left(\theta/\theta_0\right)}}{6\left(\theta/\theta_0\right)}$$

In these equations, M_0 is the moment on limit state of non-uplift, θ_0 is the angle on limit state of non-uplift, θ is the rotation angle, e is the eccentric distance of vertical load, B is the foundation width, D is the foundation length, V_0 is the dead weight (considering buoyancy), and p_s is suction. M_S can be represented as follows.

$$\frac{M_s}{M_0} = 9\frac{BDp_s}{V_0}\left(2\frac{e}{B} - 3\left(\frac{e}{B}\right)^2 - \frac{1}{4}\right) \tag{3}$$

Thus, from Eqs. eq(1), eq(2) and eq(3), M can be represented as

$$\frac{M}{M_0} = -\frac{9}{4}\frac{BDp_s}{V_0} + \left(6 + 15\frac{BDp_s}{V_0}\right)\frac{e}{B} - 9\frac{BDp_s}{V_0}\left(\frac{e}{B}\right)^2$$

Fig.15 shows the relationship between the moment and its rotation angle, according to the original equation and the corrected equation. The corrected equation predicts a higher resistance moment, with the result that a lower rotation angle is required to obtain the same moment. **Fig.16** shows the predictions by the two equations for the eccentric distance and the angle of rotation. The corrected equation gives lower values for the eccentric distance due to the suppression of overturn by suction.

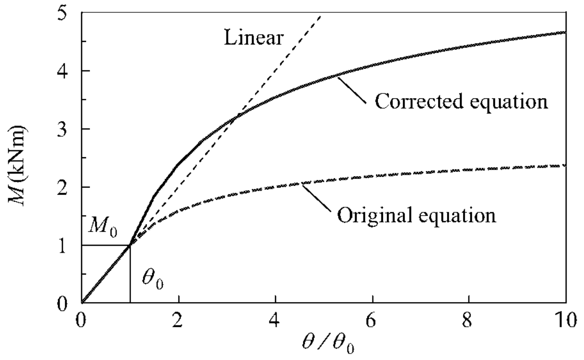

Fig.15 The Moment and its rotation angle

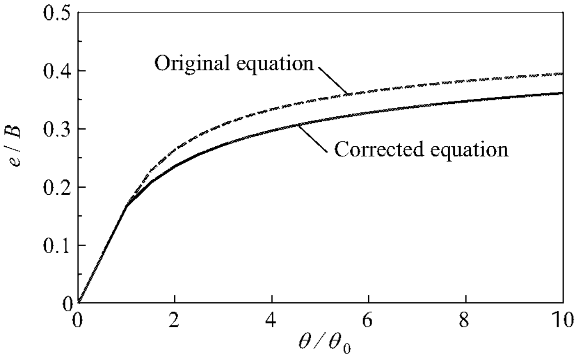

Fig.16 The eccentric distance and the angle of rotation

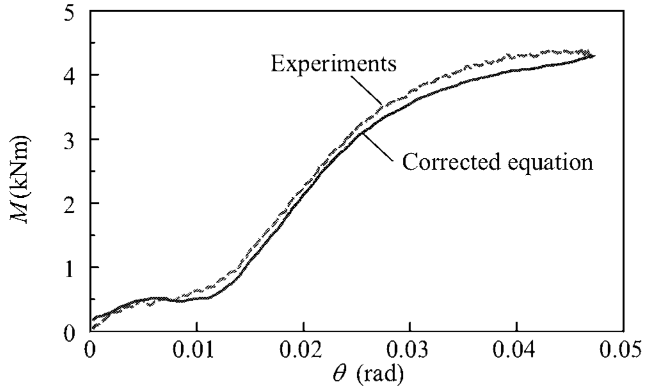

Fig.17 The relationship between the resistance moment and rotation angle calculated using the corrected equation

(3) Validation of the corrected equation

Experiments were carried out in order to validate the corrected equation. **Fig.17** shows the resistance moment observed in case C35 and the relationship between the resistance moment and rotation angle calculated using the corrected equation. Here, the mean of the measured values observed at pressure meters W1-W6 in **Fig.3** was used for p_s in eq(4). The coefficient of elasticity for the concrete blocks (E_c = 2.35 × 10^7 kN/m^2) used to model the ground was also used for the coefficient of deformation of the ground in calculating θ_0. The moment given by the corrected equation very closely resembles the moment observed in case C35. It was therefore judged that the corrected equation is valid.

(4) Verification of conditions during uplift of foundation by dynamic analysis

When using the corrected equation, the condition beneath the underside of the foundation must satisfy the vacuum condition (Condition B), which was assumed during the derivation of the equation. If water flows under the foundation during uplift, this changes the water conditions in response to the continuing movement of the foundation. Dynamic suction effects during foundation movement must also be analyzed.

Since there do not currently exist any tools for estimating the characteristics of changes in water resistance during foundation movement, the analytical model was replaced with a dynamic model that assumes Condition B in the foundation structure designed using the corrected equation, and the time history of the response was analyzed. This model was assessed for stability in terms of foundation response and water conditions. Here, the simple model shown in **Fig.18** was employed. The vertical springs were assumed to be bi-linear, with the constant K_V representing the ground during compression, and the constant K_{SUC} representing the suction

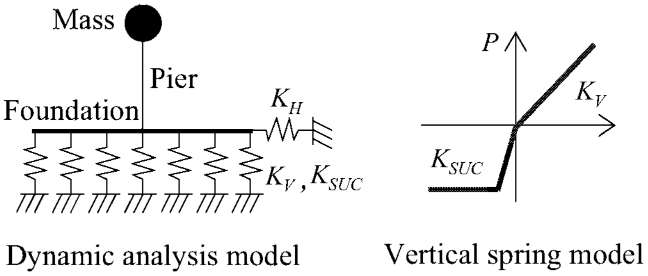

Fig.18 The dynamic analytical model

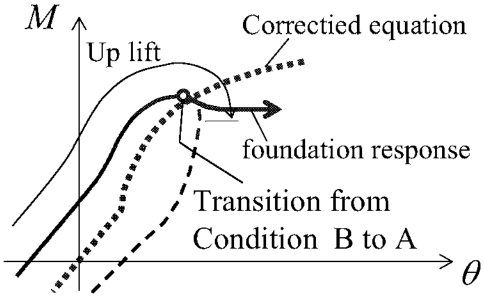

Fig.19 Transition Condition B to A

during extension. The time history of the response of this model was prepared and the volume beneath the foundation V and the inflow water volume Q were calculated. Bernoulli's equation was used for calculating Q. The inflow speed v based on the difference between the static water pressure and the vacuum is as follows.

$$v = \sqrt{2g\,(h + p_a/w)} \tag{4}$$

Where g is gravitational acceleration, h is water depth, p_a is atmospheric pressure, and w is the weight of water per unit volume. Inflow water volume V is v multiplied by the entrance area and time. Condition B is obtained when $V > Q$, and there is a vacuum beneath the foundation.

When Condition B transitions to Condition A during uplift of the foundation, the moment operating on the foundation due to suction disappears temporarily, and it is possible for the response of the foundation to become unstable (**Fig.19**). It is therefore necessary to verify whether V remains greater than Q during the rotation process. When the transition from B to A occurs while the foundation is descending, the water pressure, which was decreasing, rises quickly to a high value, exceeding the static water pressure. However, this pressure does not act to lift the foundation (if it did, the water pressure would fall back to a low level), and as such the response of the foundation is not expected to become unstable in this case. Here, the support situation changes quickly to support only by the ground, and it is possible for the ground to reach a critical condition, therfore, this ground condition must also be verified.

Fig.20 presents the results of a dynamic analysis of a spread footing (dimensions, 10 m × 10 m; dead weight, 48,000 kN; water depth, 5 m) designed using the corrected equation. The maximum resistance moment, as determined by the critical soil values (maximum ground reaction, 1,500 kN/m^2) is 155,750 kNm, if the effect of suction (Condition B) is considered, and 137,600 kNm, if suction is neglected. Since transition of the condition beneath the foundation from B to A would occur while the foundation is descending, and the response moment is less than the maximum resistance moment that would occur under either condition, it was found that this

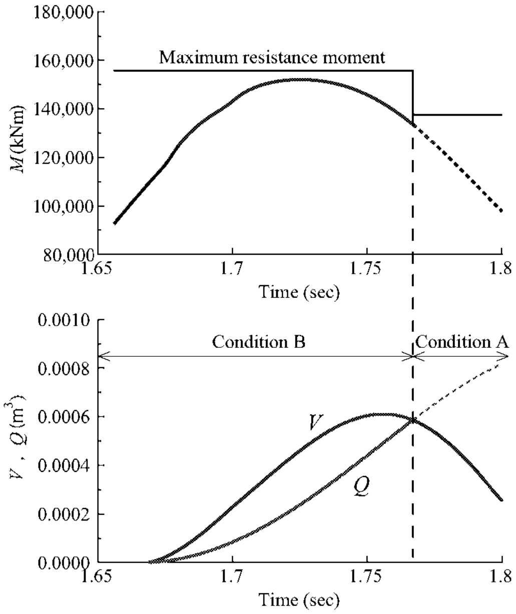

Fig.20 The results of a dynamic analysis and the maximum resistance moment

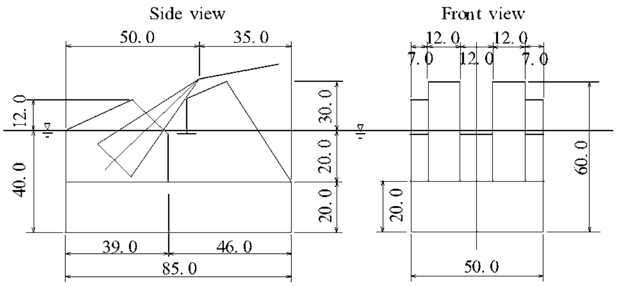

Fig.21 The anchorage for a suspension bridge (preliminary design)

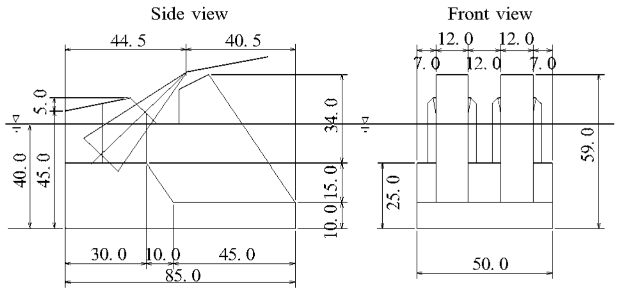

Fig.22 The anchorage for a suspension bridge (taking account of suction effects)

foundation is stable.

(5) Example of seismic design with consideration of suction

A preliminary design for the highway project on entrance of bay area[3)] had been carried out (**Fig.21**). Authors designed the anchorage for this suspension bridge, taking account of suction effects. **Fig.22** shows the structure with consideration of suction, and **Table 2** provides the calculated and observed results of a stability check during an earthquake. Here, since the foundation dimensions were determined by standard loading and other structural dimensions were determined by the anchor frame, saddle dimensions, installation location and other parameters in the preliminary design request, there was a certain safety margin in bearing capacity and sliding parameters during an earthquake. The shape of the underside of the foundation was set the same as that in the original, however the weight of the body was varied such that bearing capacity and safety factor for sliding were consistent with those of the original preliminary design, with due consideration given to the anchor frame and saddle dimensions and locations. Since the resistance moment was found to be higher than that in the conventional design method, due to the effects of suction, it was possible to lighten the body. This allowed an approximately 20% reduction in the volume of concrete used for the body.

The following results were obtained in the seismic design taking account of suction:

- In order to employ the ultimate bearing capacity equation while considering the eccentricity and slope of the loads, high bearing capasity are assumed, since suction decreases the eccentric distance of vertical

Table 2 The calculated and observed results

		Unit	Preliminary design	Account suction
Bottom force	Vertical force	MN	1,646	1,875
	Horizontal force	MN	1,875	1,959
	Moment	MN·m	53,798	51,607
Bearing check	Ultimate bearing capacity	MN	5,368	6,744
	Safety ratio (¿2.0)	–	3.26	3.6
Sliding check	Resistance force	MN	4,417	5,173
	Safety ratio (¿1.2)	–	2.36	2.64

load. This increases the stability with respect to the vertical load.

- The horizontally acting force also increases with the increase in resistance moment due to suction. However, since the horizontal friction force is also increased by the augmented vertical force, the stability against sliding is actually improved.

It was verified that the design of structures such as bridge footings can be economized by considering this suction phenomenon.

5. Summary

The following results were obtained in laboratory experiments and through a test design taking account of the effects of suction on underwater bridge footings.

- Two conditions (A and B) may occur during tilting of a foundation, depending on the volume of the space under the foundation and the volume of inflow from the surrounding water. A near-vacuum condition is obtained under Condition B, this condition allows for the creation of seismic designs that take advantage of the effects of suction.
- The corrected equation described here allows for the design of a smaller foundation than that required by the conventional original equation.
- Suction acts only briefly during uplift of foundations constructed on permeable ground such as sandy soil due to permeation flow into the space immediately beneath the foundation. There is a danger of boiling if the permeation flow is high, and this must be investigated further.
- It is anticipated that this effect will be advantageous for foundations in deep water, as the resistance moment due to suction increases with depth.
- Under repeated loading, it is anticipated that water entering the space between the foundation and the ground may remain in place when the foundation descends, reducing the resistance of the structure to sliding. It is therefore necessary to investigate sliding resistance in more detail.
- The maximum suction is maintained at a near-vacuum level, independent of the foundation rotation speed, when a flow-blocking strip is installed along the bottom edge of the foundation. It is therefore desirable to propose not only more economical foundation design methods, but also structural configurations that will maximize the effects of suction.

References

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