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Characteristics of Wave Exciting Forces on a Very Large Floating Structure with Submerged-Plate

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In this study, we focus on the submerged plate built into the Very Large Floating Structure with the partial openings of 5m long, which enables the reverse flow of incident wave to generate the wave breaking. The purpose of this study is to investigate the characteristics of wave exciting forces acting on the submerged plate and the fore part of VLFS. Firstly, we have carried out the extensive experiments to understand the characteristics of the wave exciting forces. Then we have performed the numerical simulations by applying the Marker and Cell method (MAC method) and compared with the experimental results. We discuss the validity of MAC method and the effects of the submerged plate on the motion of VLFS. As a result, we get the conclusion that the submerged plate is useful for reducing the wave exciting forces acting on the structure behind the submerged plate.

Key Words : Marker and Cell Method, Submerged-Plate, VLFS, Wave Exciting Forces

1. Introduction

The hydroelastic displacement of a Very Large Floating Structure (VLFS) is the largest at its weather side. If the response amplitude of VLFS became smaller at the weather side, the hydroelastic deformation would be decrease. The characteristic of hydroelastic response is regarded as the characteristic of energy propagation in waves (Ohta et al., 2002). The energy of propagation wave consists of incident wave energy, reflection wave energy and dissipation wave energy. It is considered that the increase of dissipation wave energy and the decrease of incident wave energy will reduce the energy of the propagation wave. The breaking wave induced by the submerged plate is a typical example of the dissipation wave energy. In order to reduce the undesirable deflection of VLFS, a device has been developed, which is the submerged plate attached to the weather side of VLFS with a clearance gap. Takaki et al. have studied the performance of the breakwater systems experimentally and theoretically using the submerged horizontal plate (Takaki and Lin, 2000). The basic mechanism of dissipating wave energy was shown in Takaki's studies. Namely, when the incident wave propagates into the submerged plate, the flow due to the wave is accelerated around the fore edge of the plate, while the strong reverse flow is generated at the aft edge. These two opposite flows collide each other, as a results, wave breaking and wave fission dissipate the incident wave energy. The performance of the submerged plate type breakwater was found to be quite sensitive to the submerged depth. In this study, we focus on the submerged

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plate built into the VLFS with the partial openings of 5 m long, which enables the reverse flow of incident wave to generate the wave breaking. Kong et al.(2004) investigated the characteristics of radiation forces on the submerged plate heaving near a free surface without the VLFS using the composite grid method. The characteristics of wave exciting forces acting on the submerged plate and the fore part of VLFS are investigated in this study. Firstly, we have carried out the extensive experiments to make clear the characteristics of the wave exciting forces acting on the submerged plate and the fore part of VLFS. Then we have performed the numerical simulations by applying the Marker and Cell method (MAC method) and compare with the experimental results. We discuss the validity of MAC method and the effects of the submerged plate on the motion of VLFS.

2. Experimental Tank Test

The experiments were carried out in the two-dimensional wave tank, which is 42 meters in length, 1.2 meters in breadth and 2 meters in depth. The test setup is shown in Fig. 1. The submerged plate is supported by four shafts of diameter 10 mm, and VLFS is replaced with four box type floating units ($L \times B \times d = 0.9 \times 1.18 \times 0.04$ m). We assume that the fore end part of VLFS is corresponding to the first float unit in the weather side. We measured the wave exciting forces for heave acting on the submerged plate as well as the fore part of VLFS with/without submerged plate. We performed the extensive experiments to understand the characteristics of the wave exciting forces by using the 1/50 scale model of the submerged plate. The principal particulars of the submerged plate and the experimental conditions are shown in Table 1. It also shows the actual sea conditions corresponding to the experimental conditions. The tests were done every 0.141 seconds from the period of 0.989 to 2.828 seconds in regular waves with the wave amplitude of 10 mm and 30 mm, respectively. These experimental data were analyzed by means of Fourier series. The components from

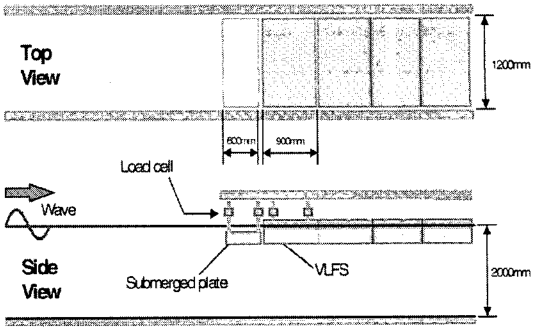

Fig. 1 Test setup for the wave exciting force test

Table 1 Principal particulars of submerged plate and experimental conditions

	Actual plate	Model [1/50]
Water depth	100 m	2 m
Length of plate	30 m	600 mm
Thickness of plate	1 m	20 mm
Submerged depth of plate	2 m	40 mm
Wave amplitude	0.5 m, 1.5 m	10 mm, 30 mm
Wave period	7-20 sec (every 1sec)	0.989-2.828 sec (every 0.141 sec)

the first to the fifth order are shown in the figures.

The non-dimensional forms of the wave exciting forces are as follows,

$$\text{Heaving force}: \hat{F}_z = F_Z / \rho g \zeta_a BL \qquad (1)$$

where the symbols ρ, g, ζ_a, L, and B are the fluid density, gravity acceleration, wave amplitude, length of submerged plate, and breadth of submerged plate.

3. Numerical Scheme

3.1 Computational procedure

We have performed the numerical simulation based on the MAC method. The governing equations which are the Navier-Stokes equation and the continuity equation in the case of two-dimensional, incompressible and viscous fluid are represented as follows,

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \qquad (2)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z} = -\frac{\partial \phi}{\partial x}+v\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{3}$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z} = -\frac{\partial \phi}{\partial z}+v\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial z^2}\right)+g \tag{4}$$

Here the Cartesian coordinate system (x, z) is employed and velocity components are u, w in respective direction. ϕ is the pressure divided by the fluid density and v is the kinematic viscosity. The computational domain is discretized into a staggered rectangular inflexible mesh system with constant spacing in the horizontal direction while variable in the vertical one in order to have finer mesh near the body and the free surface. The computational procedure is similar to the modified TUMMAC method (Lee et al., 1990).

The calculation proceeds through a sequence of loops each advancing the entire flow configuration through sufficiently small time increments Δt which satisfy the stability criteria posed by Courant Number. An Euler explicit time stepping scheme is used for the time marching procedure.

The pressure field at the n-th time step is obtained by iteratively solving the following Poisson equation which is derived by taking the divergence of velocities and set it to zero at the $(n+1)$th time step.

The Poisson equation is solved as the boundary value problem by the Successive Over Relaxation (SOR) method except in the boundary cells, and it is iteratively solved by using

$$\Phi^{m+1}=\Phi^m+\omega(\Phi_{cal}^{m+1}-\Phi^m) \tag{5}$$

where ω represents the relaxation factor and superscript indicates the number of iteration. Iterations are stopped when the pressure difference between two consecutive approximations is smaller than a certain quantity ε, chosen in advance. The cycle is repeated until the number of time steps reaches the predetermined value.

The finite-difference scheme for the convective terms must be carefully chosen, since it often renders decisive influences on the results. In this study, a third-order upwind scheme with variable mesh size is employed for the fluid domains. In the vicinity of the boundaries, where sufficient numbers of velocity points are not available, the combination of a second-order centered and donor cell scheme is used depending on the number of available velocity points. On the other hand, the second-order centered scheme is employed for the diffusive terms. The second-order Adams-Bashforth method is used for the time differencing.

3.2 Free-surface conditions

The dynamic and kinematic free-surface conditions are written as

$$\phi=\phi_0=0 \text{ on } z=\eta \tag{6}$$

$$\frac{D(\eta-z)}{Dt}=0 \text{ on } z=\eta \tag{7}$$

where η is the wave height and ϕ_0 is the atmospheric pressure divided by the density of fluid. The viscous stress and surface tension on the free-surface are neglected in this study. As it was already proved by Hinatsu (1992), the tangential stress at the free-surface affects the results extremely slightly and it can be neglected for the flow around the body.

The dynamic condition expressed by Eq. (6) is fulfilled in the procedure of pressure computation described below, and the kinematic condition expressed by Eq. (7) is fulfilled by the Lagrangian movement of the segments that form the free-surface configuration. The two end-points of each segment are located on the underlying lines of the rectangular cell system. Since their coordinates are defined in two dimensions, this use of segments enables the expression of a free-surface configuration. The end-points of the segments are moved in the following Lagrangian manner as the marker particles of the MAC method (Welch et al., 1966),

$$\begin{aligned} x^{n+1}&=x^n+\Delta t\cdot u \\ z^{n+1}&=z^n+\Delta t\cdot w \end{aligned} \tag{8}$$

Here, (x^n, z^n) is the location of the end points of the old segment and the new segment is temporarily determined by (x^{n+1}, z^{n+1}). Then, the new end-points are determined from the crossings of the temporary segments with the underlying mesh lines. The velocity vector (u, w) for the movement of the end-points is given by linear interpolation from the neighboring velocities.

The dynamic free-surface condition of Eq. (6) is implemented by the irregular star technique (Chan and Street, 1970) in the solution process of the Poisson equation for the pressure. The irregular star technique means that the finite difference formula for Poisson equation was applied for five points spaced irregularly including one or two free-surface nodes where the pressure is the same as atmospheric pressure.

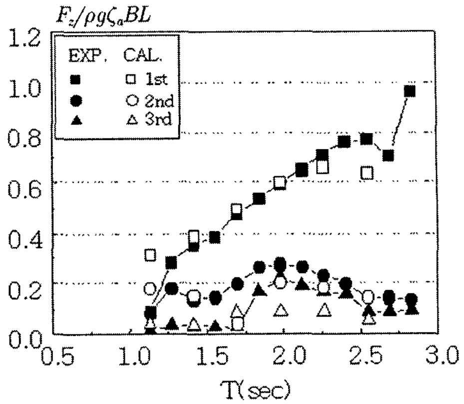

Fig. 2 Wave exciting forces on VLFS with sub-plate ($\zeta_a=30$ mm)

3.3 Other boundary conditions

At the inflow boundary of the computational domain, a numerical wavemaker is established by prescribing the inflow velocities based on the linear theory, the inflow velocities are given as follows,

$$u_{\frac{1}{2},k}=\omega\zeta_a\frac{\cosh K(h+ZP_k)}{\sinh(Kh)}\sin\left(\omega t+K\frac{DX}{2}\right) \quad (9)$$

$$w_{1,k+\frac{1}{2}}=\omega\zeta_a\frac{\sinh K\left(h+ZP_k-\frac{1}{2}DZ_k\right)}{\sinh(Kh)}\cos(\omega t) \quad (10)$$

where ζ_a is the wave amplitude, ω is the angular frequency, K is the wave number and h is the depth of region.

At the bottom boundary of the computational domain, the free-slip boundary conditions are given for the velocity, and the zero-normal gradient condition is imposed for the boundary condition of pressure.

In the present study, the added dissipation zone method is employed as the wave absorbing condition at the outflow boundary. Inside the damping zone, the mesh size is gradually increased in the horizontal direction to provide additional numerical damping.

4. Results and Discussion

We have validated the MAC method by the comparison of hydrodynamic forces on the fore part of VLFS with the experimental results. Figure 2 shows the wave exciting forces for heave on the fore part of VLFS with the submerged plate obtained by the present numerical calculations and experiments. Numerical results are in good agreement with not only the experimental ones with the first order component but also the ones with the second and third order components. From this comparison, we can say that the MAC method is adequate to estimate the non-linear hydrodynamic forces on the complex formed structure such as the float with the submerged plate.

4.1 Discussion of wave exciting forces on VLFS

Figures 3 and 4 show the first order components of the wave exciting forces for heave acting on the fore part of VLFS. Figure 3 corresponds to the results with the wave amplitude of $\zeta_a=10$ mm, and Fig. 4 is the results with $\zeta_a=30$ mm. Firstly, we discuss the wave amplitude effect on the wave exciting forces on the fore part of VLFS with and without the submerged plate. The non-dimensional values without the submerged plate show almost the same values irrespective of incident wave amplitudes because there is no non-linear wave such as breaking waves. However, the wave exciting forces with the submerged plate decrease much less than the ones without it in the condition with the large wave amplitude of $\zeta_a=30$ mm and the short wave periods because of breaking waves. While, in the case with small wave amplitude of $\zeta_a=10$ mm, they do not decrease as much as the ones large wave amplitude around the wave period of 1.0 second, because most of the incident waves pass through the upper domain of the submerged plate in this condition. Furthermore, as the wave periods become longer, the values of wave exciting forces on VLFS with the submerged plate become closer to the ones without it. This illustrates why the long waves pass through the submerged plate without breaking waves. The numerical values denoted with the circle ○ are in good agreement with the experimental ones irrespective of the wave amplitudes.

4.2 Discussion of wave exciting forces on submerged plate

Figures 5 and 6 show the wave exciting forces for heave acting on the submerged plate. The experimental results show the first order component to the fifth order component. Figure 5 corresponds to the results with the wave amplitude $\zeta_a=10$ mm, and Fig. 6 is the results with $\zeta_a=30$ mm.

Even though the violent wave breaking phenomena have occurred above the submerged plate in the experiment, it has to be noticed that the first order components are dominant in comparison

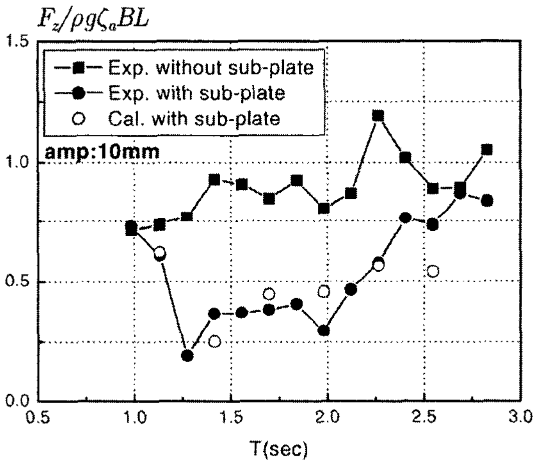

Fig. 3 Wave exciting forces on VLFS with/without submerged plate ($\zeta_a=10$ mm)

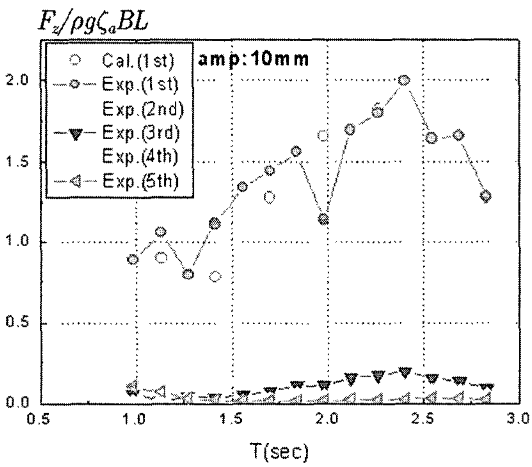

Fig. 5 Wave exciting forces on submerged plate ($\zeta_a=10$ mm)

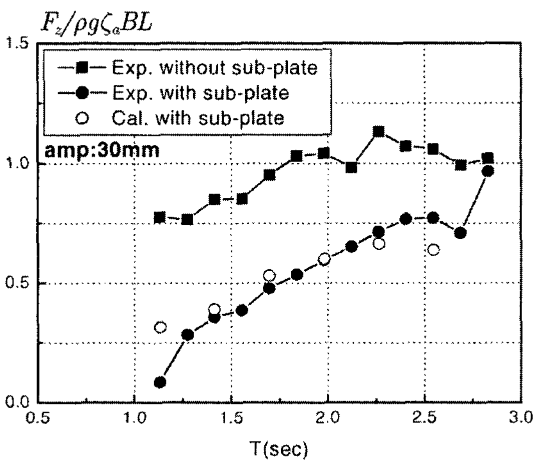

Fig. 4 Wave exciting forces on VLFS with/without submerged plate ($\zeta_a=30$ mm)

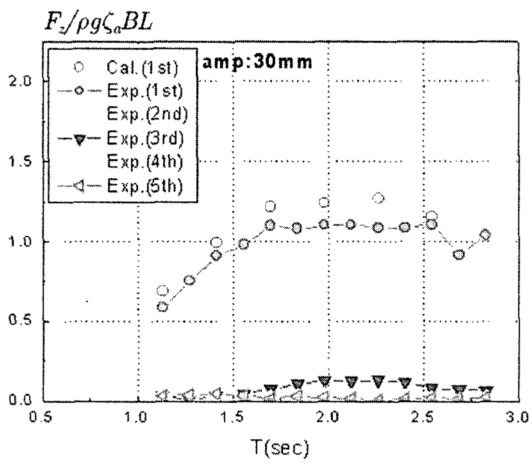

Fig. 6 Wave exciting forces on submerged plate ($\zeta_a=30$ mm)

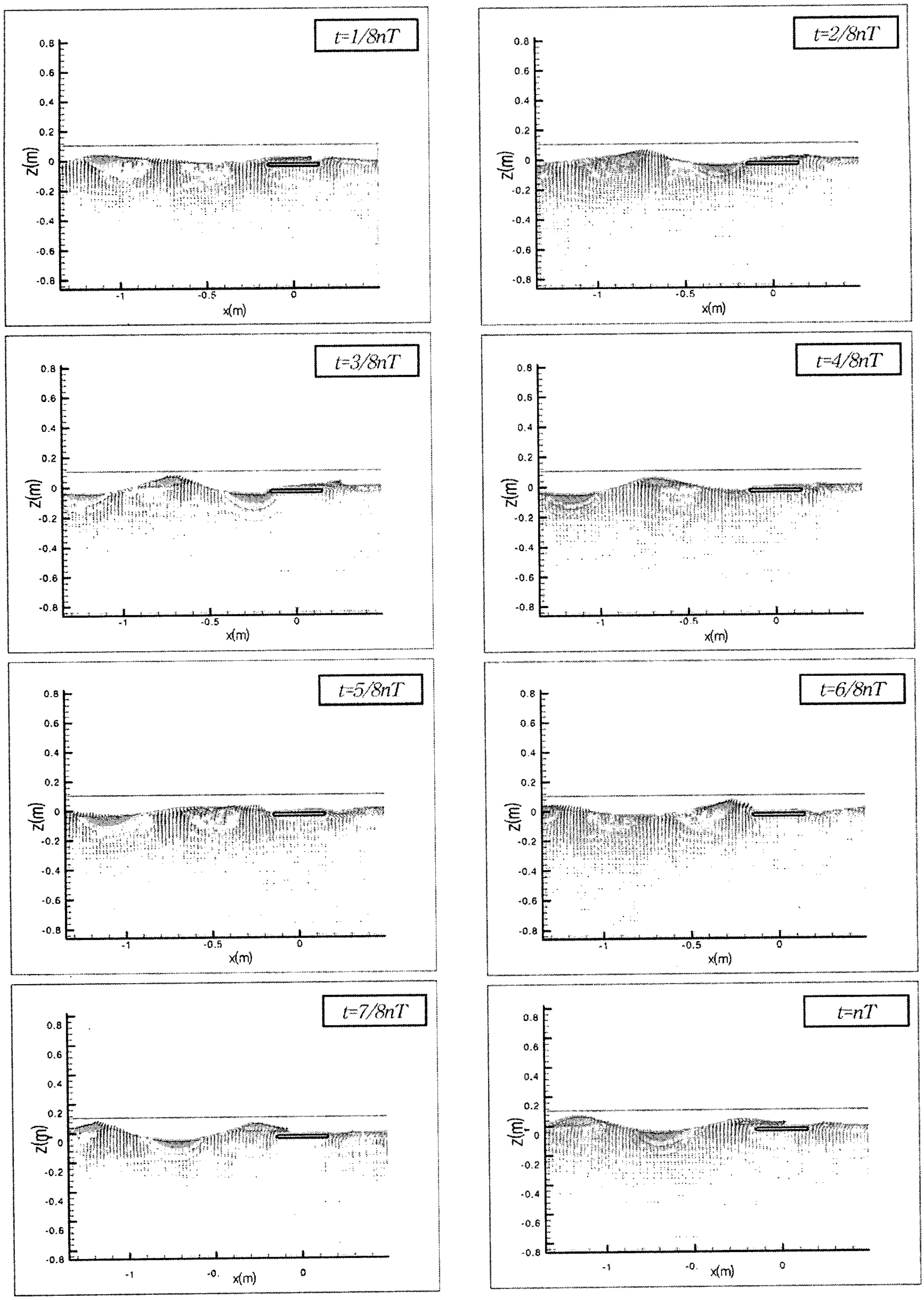

Fig. 7 Velocity vector field and pressure contour around submerged plate for T_w=0.8 sec

with the ones on VLFS with submerged plate (see Fig. 2). Therefore, we may say that the wave fission due to the breaking waves scarcely affects the hydrodynamic forces acting on the submerged plate, and it affects strongly the ones on the structure behind the submerged plate.

The numerical results denoted with the mark of ○ are in good agreement with the experimental ones irrespective of the wave amplitudes, and the wave exciting forces increase with the wave period.

Figure 7 shows the velocity vector fields and pressure contours around the submerged plate without the VLFS corresponding to the short wave period $T_w=0.8$ sec, submergence depth $d=$ 20 mm, and wave amplitude $\zeta_a=50$ mm. From this figure, we can observe that the incident wave energy is considerably decreased due to the submerged plate. Therefore, we can estimate that the attachment of additional structure on the weather side of VLFS could bring about the reduction of propagation wave energy. As a result, the submerged plate can be expected to reduce the motion of VLFS in waves.

5. Conclusions

We have carried out the extensive experiments to understand the comprehensive characteristics of wave exciting forces acting on the VLFS with and without the submerged plate. Furthermore, we have performed the numerical simulations by applying the MAC method, and have compared them with experimental results. The main conclusions obtained in this study can be summarized as follows,

(1) The submerged plate is useful for reducing the wave exciting forces on the structure behind the submerged plate. As a result, we can confirm that the elastic deflection of VLFS could be reduced by the submerged plate built into the VLFS. In particular, it is useful for the short wave periods.

(2) We have made clear that the characteristics of the wave exciting forces on the submerged plate as well as the VLFS with and without the submerged plate.

(3) MAC method is useful method for estimating the non-linear wave exciting forces acting on the complex floating structure with the submerged plate.

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