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Seismic Design Factors for Sliding Stability of Waterfront Retaining Wall Considering Non-Breaking Waves

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ABSTRACT

In this paper, a new methodology is presented for obtaining the seismic design factors for sliding stability of waterfront retaining wall under the combined action of earthquake forces, non-breaking wave force and hydrostatic and hydrodynamic forces. Results are presented in terms of design charts, which show the variation of thrust factor (F_{Twet}), inertia factor (F_{Iwet}) and the combined dynamic factor (F_{Wwet}) with horizontal seismic acceleration coefficient (k_h) required for the seismic design of waterfront retaining wall. A detailed parametric study has been conducted by varying parameters like the height of non-breaking wave, height of the water on the sea-ward and land-ward sides of the wall, soil and wall friction angles and base friction angle. It has been observed that the required weight of the wall is increasing by about 66% as the ratio of non-breaking wave height to the depth of water on sea-ward side changes from 0.0 to 0.6.

Introduction

The common waterfront retaining walls like seawalls, bulkheads and quay walls play an important role in the safety of ports and harbors. Design of these waterfront retaining walls under seismic conditions is one of the important topics of research in earthquake geotechnical engineering. Poor performance of the many seawalls can be noticed from the past major earthquakes like Loma Prieta in 1989, Northridge in 1994, Kobe in 1995, Bhuj in 2001, South Asian Sumatra in 2004 and Tohoku in 2011. Seawalls will be continuously experiencing wave forces which are time varying in nature. Depending on the location of seawall, it can be subjected to non-breaking wave, breaking wave and broken wave. Seawall will be subjected to non-breaking waves when depth of water at the structure is greater than about 1.5 times the maximum expected wave height (Shore Protection Manual, 1984). Sainflou (1928) conducted the first theoretical study for assessment of wave loads exerted by non-breaking waves on vertical wall. Miche (1944) and Rundgren (1958) improved the work of Sainflou (1928) considering the second order terms in relation to the wave height. Kachoyan and Mckee (1985) presented the computation of non-breaking wave force on sloping seawall. Goda (2000) studied breaking and non-breaking wave forces acting on the vertical wall. Okabe (1926) and Mononobe and Matsuo (1929) did the pioneering work on seismic lateral earth pressures. Richards and Elms (1979) proposed the seismic design factors against sliding stability of retaining wall for the case of dry backfill and with no water in front of the wall. In recent past, solutions for computing seismic active earth pressures using limit equilibrium approach are given by Choudhury and Nimbalkar (2005, 2006), Choudhury et al. (2014) and Bellezza (2014). Seismic analysis of

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waterfront retaining walls had been studied extensively by Ebeling and Morison (1992), Choudhury and Ahmad (2007, 2008), Chakraborty and Choudhury (2014) and few other researchers. Choudhury and Ahmad (2010) presented the seismic design factors for sliding stability of waterfront retaining wall using pseudo-static method. However the seismic design factors against sliding stability of a seawall under the combined action of non-breaking wave force and earthquake forces were not studied in all the above mentioned research works. Hence, in the present study an attempt has been made to propose the seismic design factors for a seawall under the combined action of non-breaking wave force, hydrostatic and hydrodynamic forces and seismic active earth pressure by a conventional pseudo-static method using limit equilibrium analysis.

Method of Analysis

A typical gravity type rigid seawall with vertical face having height *h*, retaining a cohesionless backfill inclined at an angle β which is submerged with water to a height d_L is considered. The height of water on sea-ward side is d_S. For the present analysis, a non-breaking wave of incident height *H* and length *L* with its trough at the wall is considered.

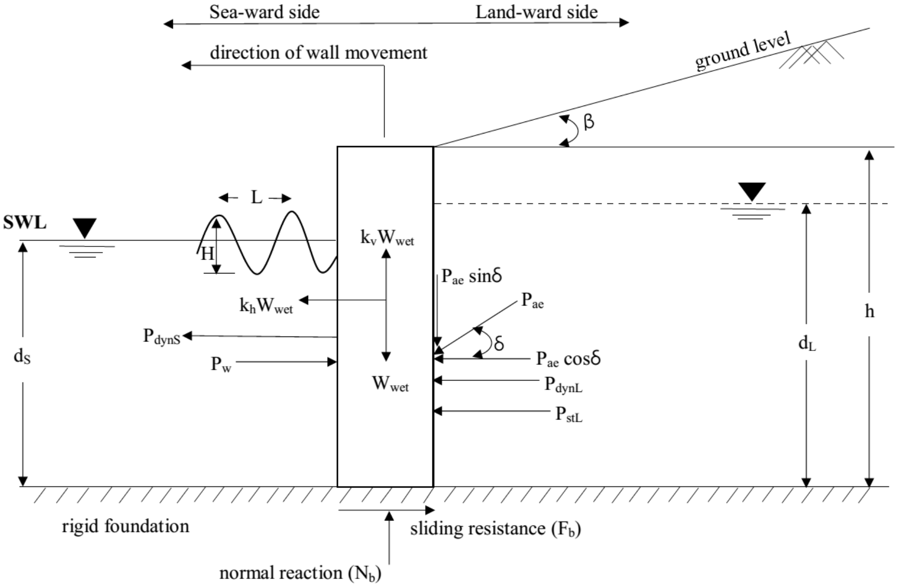

Figure 1. Details of different forces acting on seawall

The forces acting on the seawall are non-breaking wave force including hydrostatic force P_w, hydrodynamic force P_{dynS} from the seaward side, seismic active earth pressure force P_{ae}, hydrostatic force P_{stL}, hydrodynamic force from landward side P_{dynL}, weight of the wall W_{wet}, seismic inertia forces of wall $k_h W_{wet}$ and $k_v W_{wet}$ in horizontal and vertical directions respectively (with k_h and k_v as horizontal and vertical pseudo-static seismic acceleration coefficients) as shown in Figure 1. Calculations of all these above mentioned forces are summarized in Table 1.

Table 1. Forces considered in the present study.

Force	Used formulae	Reference
Total Seismic active earth pressure force	$P_{ae} = \frac{1}{2} K_{ae} \bar{\gamma} h^2 \left(1 - k_v\right)$	Ebeling and Morrison (1992)
Hydrodynamic force on land-ward and sea-ward sides considering horizontal seismic excitation	$P_{dynL}, P_{dynS} = \frac{7}{12} k_h \gamma_w \left(d_L, d_S\right)^2$	Westergaard (1933)
Hydrostatic force on land-ward side*	$P_{stL} = \frac{1}{2} \gamma_{we} (1 - k_v) d_L^2$	Ebeling and Morrison (1992)
Non-breaking wave force on seaward side*	$P_w = \frac{1}{2} (\gamma_w (1 - k_v) d_S - P_1)(d_S + h_o - H)$ $P_1 = \frac{\gamma_w H}{\cos(2\pi d_S / L)}$	Miche (1944) and Rundgren (1958)
Where $K_{ae} = \frac{\cos^2(\phi - \psi)}{\cos\psi \cos(\delta + \psi) \left[1 + \sqrt{\sin(\delta + \phi) \sin(\phi - \beta - \psi) / \cos(\delta + \psi) \cos(\beta)}\right]^2}, \quad \psi = \tan^{-1}\left(\frac{\gamma_d k_h}{\bar{\gamma}(1 - k_v)}\right),$ $\bar{\gamma} = \left(\frac{d_L}{h}\right)^2 (\gamma_{sat} - \gamma_w)(1 - r_u) + \left(1 - \left(\frac{d_L}{h}\right)^2\right) \gamma_d\ , \ \gamma_{we} = \gamma_w + (\gamma_{sat} - \gamma_w) r_u$ K_{ae} is seismic active earth pressure coefficient; γ_w is unit weight of water; γ_{sat}, γ_d are saturated and dry unit weight of soil; γ_{we}, $\bar{\gamma}$ are equivalent unit weight of water and soil due to submergence; r_u is excess pore pressure ratio; ψ is seismic inertia angle; h_o is height of mean water level above still water level		
*Modified to consider hydrodynamic force due to vertical seismic excitation by replacing the unit weight of the water γ_w by $\gamma_w(1\text{-}k_v)$ in hydrostatic force as per Chwang (1979)		

Design factors for sliding stability

Assuming that the base of the wall is rough and wall is prone to pure sliding, the relationship between shear and normal forces by considering coefficient of base friction as *tan* δ_b can be written as

$$\left(P_{stL} + P_{dynL} + P_{ae} \cos\delta + k_h W_{wet} - P_w + P_{dynS}\right) = \left(P_{ae} \sin\delta + W_{wet} - k_v W_{wet}\right) \tan\delta_b \qquad (1)$$

Solving W_{wet} by using the above equations, one can write

$$W_{wet} = P_{ae} \left(\frac{\cos\delta - \sin\delta \tan\delta_b}{\tan\delta_b (1 - k_v) - k_h}\right) + \left(\frac{P_{stL} + P_{dynL} + P_{dynS} - P_w}{\tan\delta_b (1 - k_v) - k_h}\right) \qquad (2)$$

If $W_{stat} = \left(\frac{1}{2} K_a \bar{\gamma}_s h^2\right)\left(\frac{\cos\delta - \sin\delta \tan\delta_b}{\tan\delta_b}\right)$ is the weight of the wall needed to maintain the sliding stability under static condition, then the combined dynamic design factor (F_{Wwet}) for the seawall in wet condition using the methodology of Richards and Elms (1979) can be written as

$$F_{Wwet} = \frac{W_{wet}}{W_{stat}} = F_{Twet}.F_{Iwet} + \frac{\left(\dfrac{P_{stL} + P_{dynL} + P_{dynS} - P_w}{\tan\delta_b(1-k_v) - k_h}\right)}{\left(\dfrac{1}{2}K_a\bar{\gamma}_s h^2\right)\left(\dfrac{\cos\delta - \sin\delta\tan\delta_b}{\tan\delta_b}\right)} \tag{3}$$

Where

$$F_{Twet} = \text{dynamic thrust factor for the wet condition} = \frac{K_{ae}\bar{\gamma}(1-k_v)}{K_a\overline{\gamma_s}} \tag{4}$$

$$K_a = \frac{\cos^2\phi}{\cos\delta\left[1+\sqrt{\sin(\delta+\phi)\sin(\phi-\beta)/\cos\delta\cos\beta}\right]^2} \tag{5}$$

$$\bar{\gamma}_s = \left(\frac{d_L}{h}\right)^2(\gamma_{sat} - \gamma_w) + \left(1-\left(\frac{d_L}{h}\right)^2\right)\gamma_d \tag{6}$$

$$F_{Iwet} = \text{wall inertia factor for the wet condition} = \frac{\tan\delta_b}{\tan\delta_b\left(1-k_v\right)-k_h} \tag{7}$$

Results and Discussions

One can determine the weight of the wall W_{wet} using the proposed Equation 3, which gives combined dynamic design factor (F_{Wwet}). Results are presented by graphs for a set of particular input parameters in non-dimensional form for design factors F_{Twet}, F_{Iwet} and F_{Wwet} with respect to horizontal seismic acceleration coefficient. It should be noted that, for the parametric variation, the values of non-dimensional parameters, ratio of height of mean water level above still water level to height of incident wave (h_o/H) and ratio of depth of water at structure to the wave length (d_S/L) are considered as 0.51 and 0.10653 respectively, but in reality these values can be calculated by knowing the time period of non-breaking wave and ratio of incident wave height to depth of water at structure. The value of F_{Twet} is independent of non-breaking wave height (H), depth of water on sea-ward side (d_S) and base friction angle (δ_b). Also, the values of F_{Iwet} did not depend on non-breaking wave height (H), depth of water on both sides of the wall (d_S, d_L) and wall friction angle (δ). So, these values remain constant when the above mentioned parameters are varied. Effects of various parameters on seismic design factors are detailed in the following sections.

Effect on non-breaking wave height (H)

The effect of non-breaking wave height (H) on the design factors F_{Twet}, F_{Iwet} and F_{Wwet} for seismic sliding stability can be interpreted from Figure 2(a). It is observed that the value of F_{Wwet}

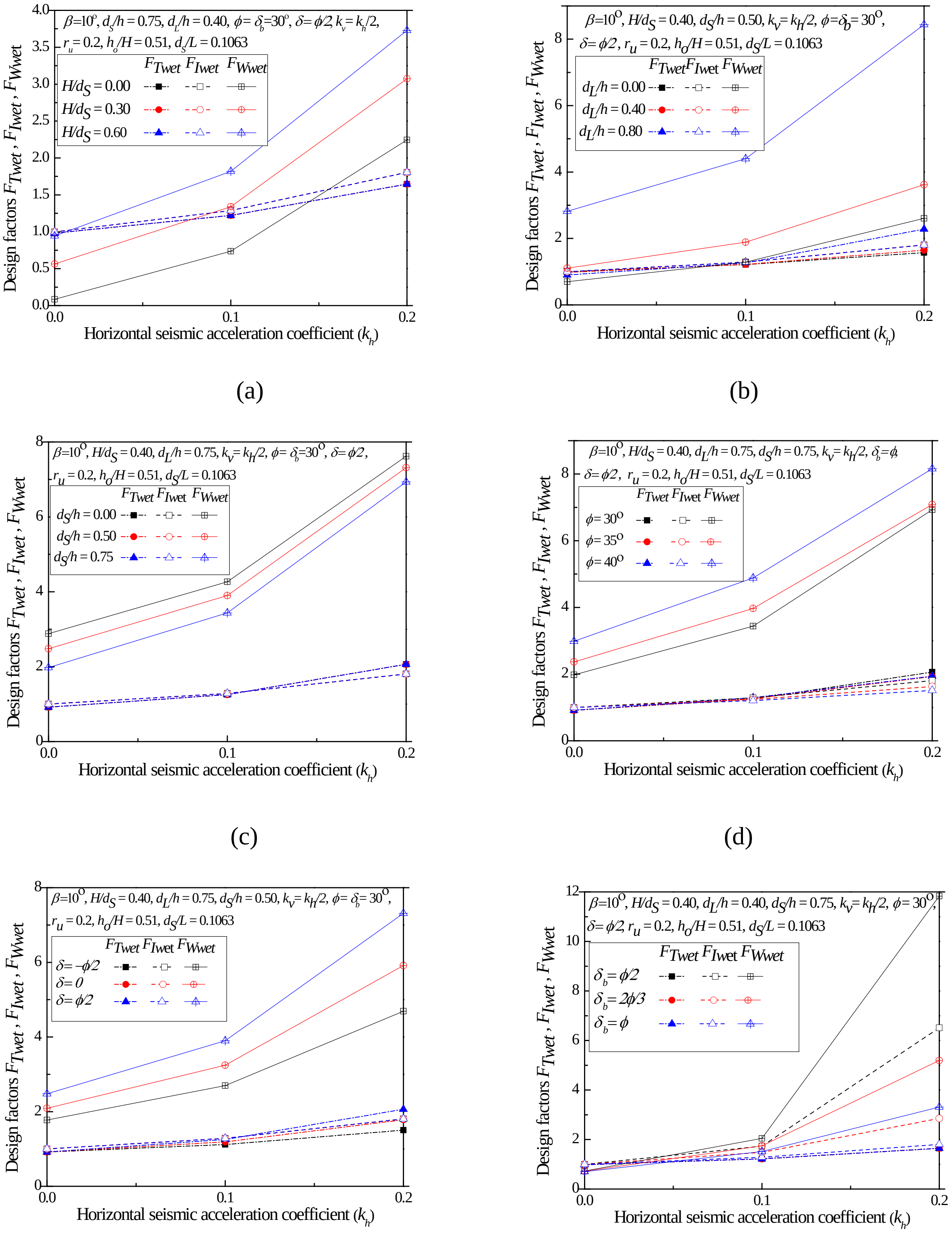

Figure 2. Variation of design factors F_{Twet}, F_{Iwet} and F_{Wwet} with H/d_S, d_L/h, d_S/h, ϕ, δ and δ_b

is found to be increasing considerably with an increase in value of H/d_S. For a typical value of k_h=0.2, when H/d_S=0 the value of F_{Wwet} is 2.245; where as the same is increases to a value of 3.728, when H/d_S=0.60 i.e., there is an increase in the value of F_{Wwet} by about 66% for an increase of H/d_S value from 0 to 0.6.

Effect of submergence of backfill (d_L)

The effect of submergence of backfill (d_L) on the three design factors for sliding stability of wall is shown in Figure 2(b). The values of F_{Twet} and F_{Wwet} are increasing significantly with the increase in value of d_L/h. For example, for k_h=0.2, When d_L/h changes from 0 to 0.80, the values of F_{Twet} and F_{Wwet} increases from 1.571 to 2.280 and 2.608 to 8.437 respectively. Hence, the wall section that would be needed under the combined action of non-breaking wave and earthquake forces is about 8 times larger than the static case.

Effect of height of water on sea-ward side (d_S)

Figure 2(c) shows the typical variation of on the design factors F_{Twet}, F_{Iwet} and F_{Wwet} for seismic sliding stability for different values of d_S, which has been presented in terms of non-dimensional parameter d_S/h. With the increase in level of water on sea-ward side, the value of F_{Wwet} is decreasing as the force due to water on sea-ward side act as a resisting force. As shown in Figure 1(c), with increase in d_S/h value from 0.00 to 0.75, for k_h=0.2, the value of F_{Wwet} reduces from 7.621 to 6.932.

Effect of soil friction angle (ϕ)

It can be observed from the Figure 2(d) that, for a typical value of k_h=0.2, as the soil friction angle (ϕ) increased from 30° to 40°, the value of F_{Wwet} increased from 6.932 to 8.158. For the same data, the value of F_{Iwet} decreases from 1.81 to 1.51 and the trend of F_{Twet} depend on the ratio seismic active earth pressure coefficient (K_{ae}) to the active earth pressure coefficient in static case (K_a).

Effect of wall friction angle (δ)

The typical variations of the design factors F_{Twet}, F_{Iwet} and F_{Wwet} for seismic sliding stability for different values of wall friction angle (δ) are indicated in Figure 2(e). The values of F_{Twet} and F_{Wwet} found to be increasing significantly with increase in value of wall friction angle (δ). As an illustration, for k_h=0.2 in Figure 2(e), as the value of δ increases from 0 to $\phi/2$, the values of F_{Twet} and F_{Wwet} increased from 1.784 to 2.063 and 5.914 to 7.315 respectively. So, the weight of the wall required to be stable against seismic sliding is about 24% less in smooth wall, when compared to a rough wall with a wall friction angle of $\phi/2$.

Effect of base friction angle (δ_b)

Base friction angle has a significant effect on the sliding stability of the wall. From Figure 2(f) it can be observed that as the value of base friction increases the wall inertia factor F_{Iwet} and combined dynamic design factor F_{Wwet} decreasing drastically. For $\delta_b=\phi/2$ and k_h=0.2, the values of F_{Iwet} and F_{Wwet} are 6.512 and 11.827 respectively and for $\delta_b=\phi$ these values are reduced to 1.806 and 3.312 respectively. Hence, the assumption of base friction angle in the analysis has to be made with utmost care as it makes a large difference in seismic sliding stability of the wall.

Comparison of results

The results of the present study were compared to the results of Richards and Elms (1979) and Choudhury and Ahmad (2010) in Table 2. The values of F_{Twet} and F_{Wwet} in the present study are higher than the values obtained by Richards and Elms (1979) and Choudhury and Ahmad (2010) and the values of F_{Iwet} are identical. This is expected as the studies of Richards and Elms (1979) and Choudhury and Ahmad (2010) are corresponding to dry condition and wet condition respectively and the effect of non-breaking wave force in combination with earthquake forces was not considered in their work. The values of F_{Iwet} are identical in all the three studies as it depends on neither the water present on both sides of the wall nor the non-breaking wave force acting on the wall. The expressions of the present study were exactly same as that of proposed by Richards and Elms (1979) for dry condition. Hence, it validates the use of proposed methodology for the determination of weight of the wall required for sliding stability of seawall under the combined action of non-breaking wave force and earthquake forces.

Table 2. Comparison of the design factors obtained in the present study with the work of Richards and Elms (1979) and Choudhury and Ahmad (2010) for H/d_S=0.40, d_L/h=0.75, d_S/h=0.50, $\phi=\delta_b$= 30°, $\delta=\phi/2$, r_u =0.2

k_h	k_v	Richards and Elms (1979)			Choudhury and Ahmad (2010)			Present study		
		F_T	F_I	F_W	F_{Twet}	F_{Iwet}	F_{Wwet}	F_{Twet}	F_{Iwet}	F_{Wwet}
0.00	0.00	1.000	1.000	1.000	0.884	1.000	1.898	0.902	1.000	2.478
0.1	0.00	1.263	1.209	1.527	1.096	1.209	2.842	1.294	1.209	3.793
	0.05	1.215	1.287	1.564	1.053	1.287	2.970	1.253	1.287	3.897
	0.10	1.167	1.376	1.607	1.010	1.376	3.115	1.213	1.375	4.017
0.2	0.00	1.637	1.530	2.505	1.369	1.530	4.381	1.996	1.530	6.308
	0.10	1.571	1.806	2.839	1.297	1.806	5.042	2.063	1.806	7.315
	0.20	1.522	2.205	3.354	1.230	2.205	6.008	2.486	2.204	9.557

Conclusions

This paper presents the seismic sliding stability of a typical seawall under the action of non-breaking waves. Expressions for calculating the three design factors F_{Twet}, F_{Iwet} and F_{Wwet} are proposed by using the conventional pseudo-static method. Effect of various parameters, such as, height of non-breaking wave, water level on both sides of the wall, soil and wall friction angles and base friction angle are studied. It should be noted that all the results which are presented in graphical form in this study are limited to a particular set of input parameters mentioned in the design charts. Consideration of constant excess pore pressure ratio is limitation of the present study. The weight of the wall needed to maintain stability against seismic sliding increases with the increase in the values of non-breaking wave height, depth of water on land-ward side, soil friction angle and wall friction angle and decreases with increase in the depth of water on sea-ward side and base friction angle. The values obtained in the present study were in good agreement with the available literature. Thus, the proposed design factors can be used to determine the weight of the wall required for sliding stability of the seawall under the combined action of non-breaking wave force and earthquake forces.

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