Dynamic Site-Amplification Factors and Dynamic Attenuation Factors by Dynamic Soil Mass

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SUMMARY:
Dynamic site-amplification factors derived from the dynamic soil and rock masses increase with the increase in the shear modulus, area and mass density of the rock layers, and circular frequency of soil layers; and decrease with the increase in the circular frequencies of the rock layers; shear modulus, mass densities, and the area of soil layers. Different of soil and rock layers, from one layer and up to four soil or rock layers from the earthquake sources to the surface, e.g. fresh granite, highly weathered rock, sandy or clayey soil layers, and water layer are also analyzed in detail. The vertical and horizontal dynamic site-amplification factors are calculated by spreadsheet application. New expressions of dynamic attenuation factors for rock and soil layers in vertical and horizontal directions are also proposed and compared with other currently available methods.

Keywords: Amplification, frequency, shear modulus, Poisson's ratio, density, attenuation

1. INTRODUCTION

Currently, there are so many methods to calculate the amplification factors, such as methods by Nakamura (1989), Boore and Joyner (1997), and Bazzurro and Cornell (2004); but no methods have completely taken into consideration at the same time (i) totally the effects of the six soil parameters, i.e. shear modulus, density, Poisson's ratio, frequency, area, and thickness of soil or rock layers, and (ii) energies generated from earthquakes by dynamic soil or rock masses transfer from the base sources of earthquake fault, through layers of bedrock, weathered rock, to soil and/or water surfaces. Currently, the expressions of the dynamic soil and rock masses (Truong, 1993, 2009, 2010, 2011a, b) have five soil parameters associated with each soil or rock layer, and the dynamic soil and rock masses are dynamic impedances caused by earthquakes or vibrations derived from the theory of wave propagations through an elastic half-space. Stewart et al. (2008) found that site amplification to be generally underpredicted at high frequencies and overpredicted at the elastic site period where a strong local resonance occurs and speculated that this bias results from overdamping.

The soil amplification should be characterized by a frequency-dependent amplification function, AF(f), where f is the frequency. Generally, AF(f) depends on three or four different frequencies depending on the various soil profiles, (i) not only a generic oscillator frequency of the earthquake fault as mentioned by Bazzurro et al. (2004), (ii) but also frequencies of the layer of hard rock and/or weathered rock, and (iii) the frequency of the soil layer. If the frequency of the soil layer generated by the earthquake is equal with the natural frequency of the soil layer, double resonance phenomenon could occur. There are vertical and horizontal amplification factors as currently mentioned in the literature. For example, dividing the obtained base shear or the vertical response by the product of the tower mass and maximum horizontal and/or vertical acceleration components will result in seismic amplification factors of both horizontal and vertical earthquake components (Amiri et al., 2007).

Amplification factors (AFs) could be defined in many ways by different researchers, but this paper uses two definitions: the ratio of peak ground acceleration (PGA) from spectral acceleration of the soil surface to (i) that from spectral acceleration of the weathered rock, or (ii) that from spectral acceleration of the hard rock (bedrock). Note that peak ground accelerations of the soil, weathered rock and hard rock outcrops are measured on the same level that is the surface level. There is another method which defines the dynamic amplification factor is the ratio of the dynamic rock mass and the dynamic soil mass. The amplification of the upper parts of the soil and rock layers was determined according to the classifications of the soil and rock layers based on the values of the shear wave velocities of the National Earthquake Hazards Reduction Program (**NEHRP**) procedure.

2. DYNAMIC SITE-AMPLIFICATION FACTORS

The vertical and horizontal dynamic site-amplification factors are defined as the ratio of the dynamic rock mass (**DRM**) to dynamic soil mass (**DSM**) based on the work by Truong (1993, 2009, 2010, 2011a, b), respectively, as follows:

$$F_{Az} = \frac{A_r\sqrt{G_r\rho_r}}{\omega_r s_r}\frac{\omega_s s_s}{A_s\sqrt{G_s\rho_s}} = \frac{A_r\sqrt{G_r\rho_r}}{A_s\sqrt{G_s\rho_s}}\frac{f_s s_s}{f_r s_r} \tag{2.1}$$

$$F_{Ax} = \frac{A_r\sqrt{G_r\rho_r}}{\omega_r}\frac{\omega_s}{A_s\sqrt{G_s\rho_s}} = \frac{A_r\sqrt{G_r\rho_r}}{A_s\sqrt{G_s\rho_s}}\frac{f_s}{f_r} \tag{2.2}$$

Where G = Shear modulus, ρ = mass density, A = area under vibration, f = frequency, ω = circular frequency, subscripts r and s = for rock and soil, respectively; e.g. G_r= Shear Modulus of rock; subscripts z and x are for vertical and horizontal directions, respectively; and

$$s = \sqrt{\frac{(1-2\mu)}{2(1-\mu)}} \tag{2.3}$$

Where μ = Poisson's Ratio.

The vertical and horizontal dynamic site-amplification factors could be also defined as the vertical and horizontal dynamic impedance factors, respectively. If the circular frequency and area of rock are equal to those of the soil, Eqns. (2.1) and (2.2), respectively, become

$$F_{Az} = \frac{\sqrt{G_r\rho_r}}{\sqrt{G_s\rho_s}}\frac{s_s}{s_r} \tag{2.4}$$

$$F_{Ax} = \frac{\sqrt{G_r\rho_r}}{\sqrt{G_s\rho_s}} \tag{2.5}$$

Eqn. (2.4) has been used by Boore et al. (1997) as the amplification factor (AF) in horizontal direction. For many soil sites, e.g. Class C of Boore et al., 1993 and all for soft soils, the amplification factor would be significantly larger than two, particularly at frequencies near 1Hz. The amount of amplification to be applied can be determined either analytically for a specific soil profile or empirically based on an assumed average shear-wave velocity in the top 30m (Boore et al., 1994). For the same energy of the earthquake, the thickness of the soil layer which could be mobilized is normally less than that of the rock layer, due to the principle, the stronger the materials the stronger the dynamic impedances are. Mardiross (1988) has defined the radiation damping ratio for soil deposits resting upon a rock formation as

$$D_x = \frac{G_s \rho_s}{G_r \rho_r} \tag{2.6}$$

Similarly, the vertical radiation damping ration could be as follows:

$$D_z = \frac{G_s \rho_s s_r}{G_r \rho_r s_s} \tag{2.7}$$

Bazzurro et al. (2004) have defined the frequency-dependent amplification function as

$$F_A(f) = \frac{S_a^s(f)}{S_a^r(f))} \tag{2.8}$$

Where f is a generic oscillator frequency, $S_a^s(f)$ and $S_a^r(f)$ are the 5%-damped spectral-acceleration values at the soil surface and at the bed rock, respectively.

Semblat et a. (2002) found that amplification factor is very small for low frequencies and rapidly increases above 1.0 Hz for the shallow deposit in Nice. While, Sharma et al. (2008) found that amplification factors increase with increase in frequency in the wide range 5 -13 Hz. For a uniform soil layer on elastic rock subjected to vertical shear wave, Dobry et al. (2000) have suggested the amplification factor with material damping, which is defined as the ratio of the acceleration of soil and that for rock, as

$$F_A = \frac{1}{(1/I) + (\pi/2)\beta_s} \tag{2.9}$$

Where βs = soil material damping ratio, which depends mostly on the rock motions due to soil nonlinearity and on the plasticity index of the clay (Vucetic and Dobry, 1991), e.g. 0.05; and impedance factor I is

$$I = \frac{\sqrt{G_r \rho_r}}{\sqrt{G_s \rho_s}} \tag{2.10}$$

The maximum amplification factor only occurs when the frequency of the soil layer due to earthquake is at frequency near to its un-damped fundamental frequency (Dobry et al., 2000). Note that the fundamental frequency of the soil is the lowest value of the natural frequency of the soil. For single-degree-of-freedom vibration, the amplitude-magnification factor during vibration has been defined by Richart et al. (1970) as

$$M = \left[\left(1 - \frac{f}{f_n}\right)^2 + \left(2D\frac{f}{f_n}\right)^2\right]^{-1/2} \tag{2.11}$$

When D = damping ratio, f and f_n = frequency of the soil during vibration and un-damped natural frequency of soil layer. The maximum amplitude-magnification factor is

$$M_m = \frac{1}{2D\sqrt{1-D^2}} \tag{2.12}$$

For a soil layer on rigid bedrock, the amplification function (Roesset, 1970) is:

$$F_A = \frac{1}{\sqrt{\cos^2 F + (DF)^2}} = \frac{1}{\sqrt{\cos^2\left(2\pi \frac{H}{V_s} f\right) + \left(2\pi \frac{HD}{V_s} f\right)^2}} \tag{2.13}$$

Where F = frequency factor, defined as

$$F = \frac{\omega H}{V_s} = \frac{2\pi f H}{V_s} \tag{2.14}$$

3. DYNAMIC SOIL/ROCK/WATER HEIGHTS OF SOIL, ROCK AND WATER LAYERS MOBILIZED BY EARTHQUAKES

The dynamic soil or rock heights are the mobilized thicknesses of soil and rock by earthquakes (Truong, 2009, 2010, 2011a, b) can be determined by the following equations in vertical and horizontal directions, respectively:

$$h_z = \frac{V_s}{\omega_{cz} s} = \frac{V_s}{2\pi f_{cz} s} \tag{3.1}$$

$$h_x = \frac{V_s}{\omega_{cx}} = \frac{V_s}{2\pi f_{cx}} \tag{3.2}$$

Where ω_c = circular frequency or corner circular frequency of earthquakes for soil or rock medium, subscripts z and x are for vertical or horizontal directions, f = corner frequency, and V_s = shear velocity of the soil or rock medium.

The ratio R_{fa} of the natural frequency Eqn. (3.1) and that of Saita et al. (2004) is

$$R_{fb} = \frac{2}{\pi s} A_f \tag{3.3}$$

Where A_f is the amplification factor (Saita et al., 2004). If the amplification factor A_f is equal to 1.0, the Poisson's ratio is 0.17 for cases of rock medium, then the value of Eqn. (3.3) is also equal to 1 (Truong 2011c). The amplification factors due to the lithology unit for hard rock, soft rock, hard soil, medium soil, soft soil, and very soft soil are 1, 1.1, 1.7, 2, 2.2, and 2.8, respectively (Garcia-Rodriguez et al. 2008).

The vertical and horizontal dynamic water heights of H_z and H_x of the huge water wave for the solid-air-water (**SAW**) mixture have been presented by Truong (2011d, e, and f), respectively, as follows:

$$H_z = \frac{\sqrt{B_{saw}}}{\omega_z s_{saw} \sqrt{\rho_{saw}}} \tag{3.4}$$

$$H_x = \frac{\sqrt{B_{saw}}}{\omega_x \sqrt{\rho_{saw}}} \tag{3.5}$$

Where ρ_{saw} = Mass Density of the solid-air-water (**SAW**) mixture (Richart et al., 1970; Truong, 2011d), which can determined by

$$\rho_{saw} = \frac{\gamma_w}{g}\left(\frac{Se + G_s}{1+e}\right) \tag{3.6}$$

Where γ_w = Unit Weight of Water (or sea water), S = Degree of Saturation, G_s= Specific Gravity of solid particle, g = Gravitational acceleration, e = void ratio, B_{saw} = Bulk Modulus of elasticity of solid-air-water (**SAW**) mixture, which can be determined by the Wood equation (Wood, 1930), and

$$s_{saw} = \frac{\sqrt{(1-2\mu_{saw})}}{\sqrt{2(1-\mu_{saw})}} \tag{3.7}$$

Where μ_{saw} = Poisson' ratio of solid-air-water (SAW) mixture.

The expression for wave-propagation velocity in solid-air-water (**SAW**) mixture (Richart et al., 1970; Truong, 2011d) can be defined by

$$V_{saw} = \sqrt{\frac{B_{saw}}{\rho_{saw}}} \tag{3.8}$$

4. VERTICAL AND HORIZONTAL ACCELERATIONS OF SOIL AND ROCK LAYERS

There are two ways to determine of the accelerations of the rock and soil layers: (i) direct measurements through different available equipment, and (ii) methods based on dynamic soil mass and dynamic rock mass by using the values of shear wave velocity, Poisson's ratio, and frequencies of the earthquakes. For simple cases with four layers of water, soil, weathered rock and hard rock, the vertical accelerations of the tops of hard rock, weathered rock, soil and water layers based on the dynamic soil mass and the dynamic rock mass, respectively, are

$$A_r = \frac{h_{rz}}{H_r} \tag{4.1}$$

$$A_{wr} = \frac{h_{rz}}{H_r + (H_{wr}/I_{rwr})} \tag{4.2}$$

$$A_s = \frac{h_{rz}}{H_r + (H_{wr}/I_{rwr}) + (H_s/I_{rs})} \tag{4.3}$$

$$A_w = \frac{h_{rz}}{H_r + (H_{wr}/I_{rwr}) + (H_s/I_{rs}) + (H_w/I_{rw})} \tag{4.4}$$

Where h_{rz} = mobilized rock height by earthquake in the vertical direction, H = thickness of the layer, subscripts w, s, wr and r are for water, soil, weathered rock and hard rock, respectively; e.g. Hr = thickness of the hard rock at the sea bottom, and I = Impedance factor, and subscripts rwr, rs and rw are for rock to weathered rock, for rock to soil, and for rock to water, respectively.

The acceleration of the surface of the rock outcrop is

$$A_{rs} = \frac{h_{rz}}{H_F} \tag{4.5}$$

Where H_F = depth of the earthquake fault.

The vertical dynamic soil-amplification factor without the material damping is the ratio of the acceleration of soil medium and the acceleration of rock medium at the same surface level (Dobry et al., 2000).

$$F_{Asr} = \frac{H_F}{H_r + \left(H_{wr} / I_{rwr}\right) + (H_s / I_{rs})} \tag{4.6}$$

The vertical dynamic water- amplification factor without the material damping of water is the ratio of the acceleration of water medium and the acceleration of rock medium at the same surface level.

$$F_{Awr} = \frac{H_F}{H_r + \left(H_{wr} / I_{rwr}\right) + (H_s / I_{rs}) + (H_w / I_{rw})} \tag{4.7}$$

Similarly, the horizontal dynamic water-amplification factor and dynamic water-amplification factor are also obtained by using the appropriate terms for horizontal direction in the above equations, e.g. by replacing h_{rz} by h_{rx} in order to determine the horizontal accelerations for soil or rock layers by the horizontal components of earthquakes.

5. VERTICAL AND HORIZONTAL DYNAMIC ATTENUATION FACTORS

Attenuation by both geometrical and material damping based on work by Bornitz (1931) (Richart et al., 1970), and Truong (1993, 2009, 2010, 2011a and b) is, as follows:

$$w = w_1 \sqrt{\frac{r_1}{r}} e^{-\alpha(r - r_1)} \tag{5.1}$$

Where r = distance from source to point in question, r_1 = distance from source to point of know amplitude, w = amplitude of the vertical component of the R-wave at a distance r from source, w_1 = amplitude of the vertical component of the R-wave at a distance r_1 from source, and α = the coefficient of attenuation, having dimensions of 1/distance, which can defined from Eqn. (3.1) as

$$\alpha_z = \frac{2\pi f s}{V_s} \tag{5.2}$$

Eqn. (5.2) is the expression of the coefficient of attenuation in vertical direction. Barkan (1962) suggested values of the coefficient of attenuation ranging from 0.01 to 0.04 (1/feet or 1/0.3048m) for various soils, while Richart et al. (1970) found that the range of the coefficient of attenuation is from 0.006 to 0.08 (1/feet or 1/0.3048m). But, in this case, the coefficient of vertical attenuation can be renamed as the vertical dynamic attenuation factor, because it is not constant and dependent on the frequency, shear wave velocity and Poisson's ratio of the soils. The expression of the coefficient of attenuation in horizontal direction or the horizontal dynamic factor can be expressed from Eqn. (5.2) as:

$$\alpha_x = \frac{2\pi f}{V_s} \tag{5.3}$$

The vertical and horizontal dynamic attenuation factors from Eqns. (5.2) and (5.3) increase with the increase in frequency and with the decrease in shear velocity of the soil, as also suggested by Castro et al. (2009). While Anderson et al. (1984) and Boore et al. (1997) suggested the coefficient of attenuation as follows:

$$\alpha = \pi k_o f \tag{5.4}$$

where k_o = Kappa operator, or site-dependent attenuation parameter, e.g. k_o= 0.01 for most rock sites in western North America. Oprsal et al. (2005) suggested that k_o= 0.01 for tectonically very stable regions up to k_o = 0.06, and k_o varies locally due to site conditions, but to constrain its actual value is difficult. For Basel, Oprsal et al. used k_o = 0.03 which corresponds to tectonically quieter region. For Greece, Margaris et al. (2002) used k_o = 0.05. If the coefficient of attenuation of Eqn. (5.2) is equal to that of Eqn. (5.4)

$$k_o = \frac{2s}{V_s} \tag{5.5}$$

If the coefficient of attenuation of Eqn. (5.3) is equal to that of Eqn. (5.4)

$$k_o = \frac{2}{V_s} \tag{5.6}$$

Kappa decreases with the increase in the shear wave velocity of the soils, as also presented by other researchers.

6. COMBINED DYNAMIC AMPLIFICATION-ATTENUATION FACTORS

The vertical and horizontal the combined dynamic site-amplification-attenuation factors are defined as, respectively:

$$F_{Acz} = \frac{A_r\sqrt{G_r\rho_r}}{A_s\sqrt{G_s\rho_s}} \frac{f_s s_s}{f_r s_r} e^{-\left(\frac{2\pi f s}{Vs}\right)} \tag{6.1}$$

$$F_{Acx} = \frac{A_r\sqrt{G_r\rho_r}}{A_s\sqrt{G_s\rho_s}} \frac{f_s}{f_r} e^{-\left(\frac{2\pi f}{V_s}\right)} \tag{6.2}$$

Where f = frequency of the medium, i.e. for soil or for rock layer. The expression of site-amplification factor from Quarter-Wavelength Method, which is a similar form with Eqn. (6.2), has been also presented by Hashash et al. (2010).

7. SPREADSHEETS FOR DYNAMIC SITE-AMPLIFICATION FACTORS AND DYANMIC ATTENUATION FACTORS

An Excel spreadsheet "SoilAmp-N1.xls" based on the work by Truong (1988 and 1991c) has been developed to calculate the dynamic site-amplification factors in horizontal and vertical directions with and without material damping and attenuation coefficients, and dynamic attenuation factors of rock, soil and water layers. There are many steps in calculations depending on the site profile before finally determining the site-amplification factors, mainly: (i) Ratio of the dynamic rock mass to dynamic weathered rock, (ii) Ratio of the dynamic weathered rock to dynamic soil mass (DSM), (iii) Ratio of DSM to dynamic water mass (DWM), (iv) Thicknesses of soil, rock and water layers mobilized by the earthquake through the frequency of the earthquake, (v) Ratios of heights of rock to soil, rock to weather rock, weather rock to soil, etc., and (vi) Peak acceleration of each soil or rock or water layer.

For an earthquake of 32 km depth, as the 2011 Tohoku earthquake, with the vertical and horizontal frequencies of the earthquake is 0.1 Hz, the shear wave velocity of hard rock of 3000 m/s, the soil depth of 1000m, no layers of weathered rock or ocean water, different shear wave velocities of soil classes D, C, B, and A of NEHRP classifications, e.g. 180 m/s, 360 m/s, 760 m/s and 1800 m/s; the mass density of weathered rock is 2.3 T/m3, and the damping ratio of 0.05; the amplification factors of different methods with and without damping ratio, attenuation and magnification factors, such as Boore et al. (1997), Dobry et al (2000), and the above formulas are presented in Table 7.1 and Fig. 7.1. The vertical and horizontal amplification factors without damping decrease with the increase in shear wave velocity of the soil layers and thicker sediments of soil or weathered rock. If the soil depth is 2900m for cases of Vs of 760m/s, the value of amplification factor is 1.0073, which is exactly the value obtained by Arkinson and Boore (2006) for cases with the frequency of 0.1014 Hz.

Table 7.1. Variation of amplification factors with shear wave velocities from different methods with and without damping, attenuation, and magnification factors

Vs	Boore	B-b	B-b-at.	F x	F x M	F X Mm	F z	F z M	F z Mm
180	25	8.44	8.42	1.03	0.092	10.28	1.03	0.414	10.29
360	12.5	6.31	6.3	1.028	0.5	10.28	1.027	6.43	10.28
760	5.921	4.042	4.04	1.024	3.13	10.24	1.022	1.269	10.23
1800	1.96	1.696	1.695	1.013	1.15	10.136	1.009	1.045	10.1

8. CONCLUSIONS

The dynamic site-amplification factors increase with the increase the depth of earthquake fault, the dynamic impedance factors, and thicknesses of the weathered rock, soil and water layers. The vertical and horizontal dynamic impedance factors between hard rock and soil layer increase with the increase in the area, mass density and shear modulus of the rock layer, and frequency of the soil layer; with the decrease in area, mass density and shear modulus of the soil layer, and the frequency of the rock layer. The vertical dynamic impedance factor increase with the increase in Poisson's ratio of the rock layer and with the decrease in Poisson's ratio of the soil layer. The vertical and horizontal dynamic attenuation factors in soil layers increase with the increase in the frequency of the soil layers; and with decrease in the shear wave velocity of the soil. The vertical dynamic attenuation factor decreases with the increase in Poisson's ratio of the soil layers.

Similarly, the dynamic water amplification factors and attenuation factors could also be obtained by as those for soil layers by replacing the mass density, shear velocity and Poisson's ratio of the soil layers with the appropriate mass density, bulk modulus and Poisson's ratio the soil-air-water (SAW) mixtures, respectively. The dynamic water impedance factors substantially increase with the increase in the percentage of air bubbles in the low range of percentage of air bubbles in the SAW mixtures, because the bulk modulus greatly decreases with the increasing percentage of air bubbles (Richart et al., 1970, Truong (2011d, e and f). Tsunami heights based on the dynamic water masses or dynamic water heights also noticeably reduces with the increase in percentage of air bubbles.

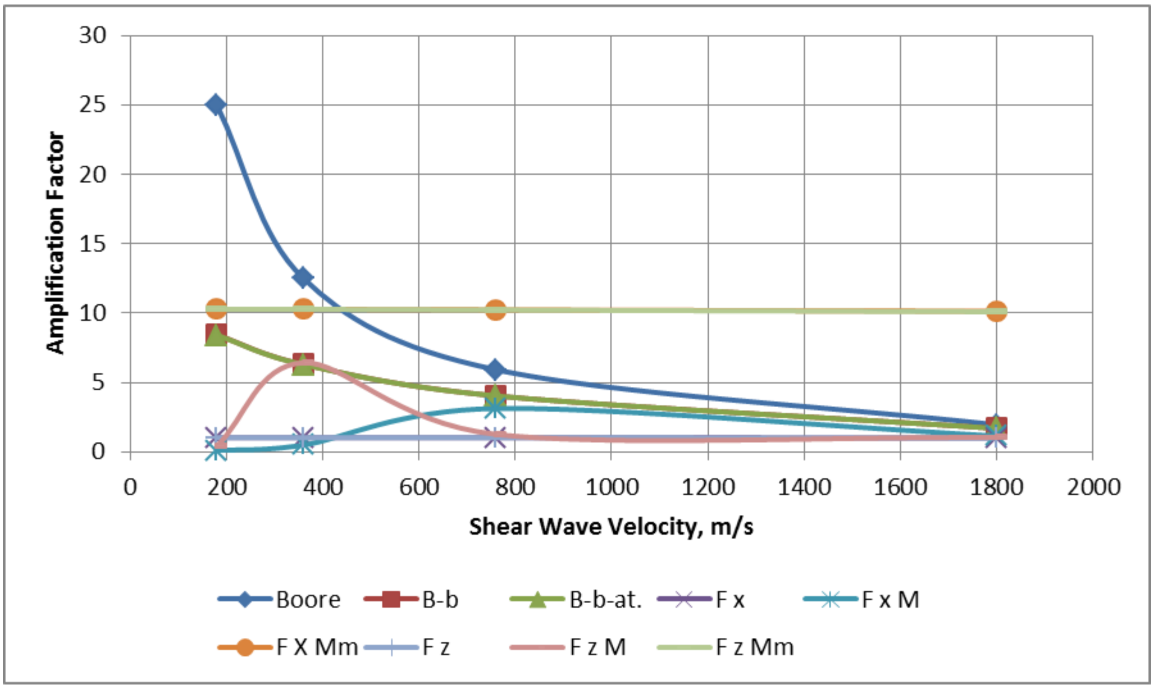

Figure 7.1. Variation of amplification factors with shear wave velocities from different methods with and without damping, attenuation, and magnification factors

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