Special Contributions, Geophysical Institute, Kyoto University, No. 6, 1966, 201-213

ON THE EARTH TIDES OBSERVED ON THE ASIAN CONTINENT AND IN THE PACIFIC AREA[1]

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(Received October 10, 1966)

Abstract

A great many observations of earth tides are being made by means of gravimeters, tiltmeters and extensometers at many stations in the world since the International Geophysical Year. But the values of three characteristic numbers on the earth tides h, k and l, related to the elastic behaviour of the earth, obtained at many stations are not always identical and regional differences are clearly recognized in the values of the characteristic numbers. A considerable divergency in their values, far in excess of observational error is also observed with time, even at one station.

Results of earth tidal observations made with gravimeters at some stations on the Asian Continent and in the Pacific Area since the beginning of the IGY, are described in the present article. Data have been analyzed by the method of least squares, the Fourier transform or the usual harmonic analysis for obtaining the gravimetric factor $G\equiv1-3k/2+h$ and the phase lag. The most reliable value of the gravimetric factor G for continental stations in Asia is 1.14 but that for oceanic ones is slightly larger. The value of the phase lag is very small for both the continental and the oceanic stations.

A regional difference between Asia and Europe is clearly found in various values related with the earth tides. It could be due to a regional heterogeneity in the elastic properties of the Upper Mantle for both continents.

1. Introduction

Tidal forces, due mainly to the moon and the sun, act on every particle of the earth. The earth is subject as a whole to tidal stresses, and it yields to them because of its elasticity. This deformation is called "tides of the solid earth" or, in short, "earth tides".

The study on the earth tides has a comparatively long history extending about a century since the first theoretical treatment by Lord Kelvin in 1863, and it became to one of the old research items. However, the study has rejuvenated by recent development of techniques in measurements and observations,

[1] Read at UMP Symposium of the Eleventh Pacific Science Congress, August 1966, Tokyo.

and it became again to an important research item for investigating the nature of the earth and its interior. Thus a great many observations of the earth tides are being made at many stations in the world since the beginning of the International Geophysical Year.

In reality, to tap the earth with great earthquakes and to twist it with the earth tides are certainly two powerful methods for diagnosing the earth's interior, and in this sense the study on the earth tides will everlastingly afford us new clues for exploring the earth and advancing our knowledge on the nature of the earth's interior.

According to the theory, if the earth were perfectly rigid, it would be possible to observe, by means of very sensitive instruments, small periodic deflections of the vertical with an amplitude of approximately 0.04 seconds and periodic variations in the intensity of gravity with that of approximately 0.2 milligals.

An observation of the gravity change caused by the earth tides can be carried out either with the help of highly sensitive gravimeters or with the aid of a high quality pendulum which can be compared with a quartz clock. It would be much easy to observe the earth tides by gravimeters than by pendulum and quartz clocks.

Observational results of the earth tides made with gravimeters at stations distributed on the Asian Continent and in the Pacific Area are briefly described in the present article.

2. Characteristic numbers on the earth tides

Change of gravity with time is generally divided into two branches. Namely, one is a periodic variation and the other non-periodic. The periodic variation of gravity is a phenomenon caused by the tide-generating forces due to the moon and the sun, and its variation is regular. The periodic gravity variation of this kind is usually referred to as the 'tidal variation of gravity'. On the other hand, the non-periodic change of gravity, if it is existing, is regarded to be related with rapid or gradual change of gravity caused by the change of state or motion of the underground material, the fluctuation of rotation speed of the earth, the crustal deformation and the like.

Now, let the potential of tide-generating force at any point on the earth due to a celestial body be denotes by W_2. W_2 is a solid harmonic function and expressed by the following formula,

$$W_2=\frac{3}{4}g\frac{M}{E}\left(\frac{a^2}{R^3}\right)r^2\left(\cos 2\theta+\frac{1}{3}\right),$$

where g is the acceleration of gravity at the earth's surface, M the mass of the celestial body, E the mass of the earth, a the mean radius of the earth, R the distance between the centre of the earth and that of the celestial body, r the radius vector from the centre of the earth, and θ the geocentric zenith distance of the celestial body.

According to the theory, if the earth were perfectly rigid, the quantity $\varDelta g_{rg}$ of the tidal variation of gravity at its point is expressed by

$$\varDelta g_{rg}=\left(\frac{\partial W_2}{\partial r}\right)_{r=a}.$$

However the real earth is not perfectly rigid but finitely elastic, and consequently it yields by action of the tide-generating force. Such being the case, the quantity $\varDelta g_{cl}$ of the tidal variation of gravity on the real earth is expressed by

$$\varDelta g_{cl}=G\cdot\left(\frac{\partial W_2}{\partial r}\right)_{r=a},$$

$$G\equiv 1-\frac{3}{2}k+h,$$

where h and k are dimensionless constants called "Love's numbers". h is related with the radial displacement of the earth's surface caused by deformation of the earth, and k the change of potential field caused by the same cause. The Love's numbers, h and k, are closely correlated with rigidity and density distributions within the earth. The symbol G is usually called "tidal factor of gravity" or, in short, "gravimetric factor".

On the other hand, the value of D which is called "diminishing factor" can be obtained from observations of deflection of the vertical with respect to the earth's crust by means of tiltmeters, or those of the amplitude of oceanic or lake tides by means of tide gauges. The diminishing factor D is expressed by the formula

$$D\equiv 1+k-h$$

using the Love's numbers h and k.

A. E. H. Love introduced such the two dimensionless numbers, h and k, to characterize various aspects of the earth tides, in 1909. T. Shida has later shown that a third number l, which is called "Shida's number", is necessary to obtain a complete representation of phenomena on the earth tides. The Shida's number l is also a dimensionless constant and related with the lateral displacement of the earth's surface caused by deformation of the earth.

Moreover, the value of L can be obtained from observations of deviation of the vertical with reference to the earth's axis measured by astronomical instruments. The factor L is expressed by the formula

$$L \equiv 1+k-l.$$

A linear combination of h and l can be obtained, with strainmeters or extensometers, from measurements of the linear strain caused by the earth tides. One of Love's numbers k can also be determined from observations of periodic fluctuations in the speed of the earth's rotation.

Consequently, if the values of G and D are determined from simultaneous observations at the same place, the numerical values of Love's numbers, h and k, can easily be determined, without any assumption on the density and elasticity distributions of the earth's interior, by combining G with D. If the value of L is furthermore determined from observations at the same place, the value of Shida's number l can also be determined by using the value of k above obtained. This is the reason why simultaneous observations with gravimeters and tiltmeters are strongly required in observations of the earth tides.

In case of a simplified earth model under the assumption that the earth is homogeneous and incompressible sphere, the following relation should be presented between the characteristic numbers,

$$k=\frac{3}{5}h \quad \text{and} \quad l=\frac{3}{10}h,$$

if, further, the rigidity is assumed to be uniform, h is expressed by the formula

$$h=\frac{5}{2}\left(1+\frac{19\mu}{2g\rho a}\right)^{-1},$$

where ρ and μ are the mean density and mean rigidity of the earth, respectively.

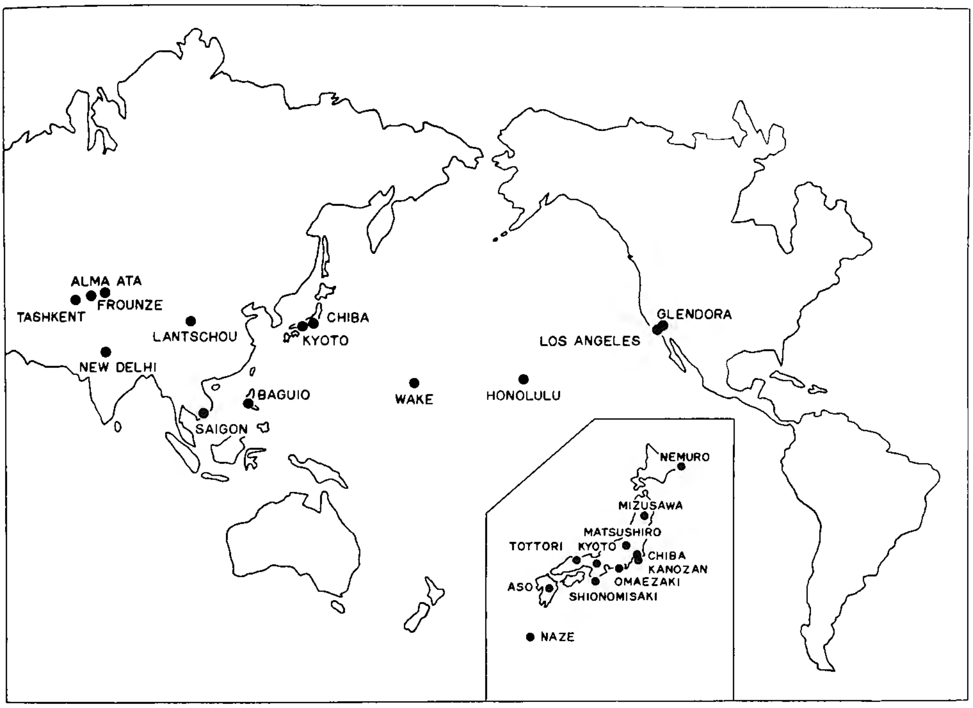
Thus, the radial displacement U observable at any point of the earth by action of the tide-generating forces is expressed by the formula

$$U=h\frac{W_2}{g}.$$

3. Observational results

The tidal variation of gravity was first observed with a gravimeter of the bifilar suspension type by W. Schweydar at Potsdam in 1914. Hence for about 50 years, observations of the tidal variation of gravity were largely developed by completion of a highly sensitive gravimeter and in combination with an automatic recording apparatus, and a great many observations were recently made at various regions of the world. The observations of the tidal variation of gravity made since the beginning of the International Geophysical Year, were especially conclusive in this field on the point of their close cooperation in simultaneous observations at various countries.

Figure shows the distribution of observation stations of the earth tides on



Gravimetric observation stations of the earth tides distributed on the Asian Continent and in the Pacific Area.

the Asian Continent and in the Pacific Area by means of gravimeters, and details of the observation stations are shown in Table 1.

Speaking in detail, observations of the earth tides made with gravimeters in Japan were divided into two series. Namely, one was one month's observations and the other one year's ones. The former was carried out at each of 10 stations in Japan; that is, Nemuro, Mizusawa, Kanozan, Matsushiro, Omaezaki, Kyoto, Shionomisaki, Tottori, Aso and Naze, by the present author [1962a] by means of an Askania gravimeter in 1957 to 1959. The one month's observations aimed mainly at investigating in detail the influence upon the tidal variation of gravity caused by difference in various conditions of observation stations; that is, the effects of oceanic tides, geological structure and others. The latter was carried out at Kyoto by the present author [1962b] by means of the same Askania gravimeter during a period of one year August 1959 to August 1960, and also at Chiba and Kanozan by the Geographical Survey Institute of Japan (Okuda [1960]) by means of another Askania gravimeter during periods of 9 months July 1957 to March 1958 and of 7 months May to December 1958, respectively. The one year's observations were made for investigating a time change in values of the tidal factor of gravity and also for determining

Table 1. Description of the observation stations and data

Station	Longitude	Latitude	Altitude	Instrument	Observation period
Kyoto	135°47′ E	35°02′ N	60 m	Askania 111	Aug. 1, 1959 – Aug. 16, 1960
Chiba	140°38′ E	35°38′ N	27 m	Askania 105	July 1, 1957 – Mar. 31, 1958
Alma Ata	76°58′ E	43°11′ N	1400 m	Askania 126 & 134	Oct. 15, 1958 – May 22, 1959
Tashkent	69°18′ E	41°20′ N		Askania 126 & 134	Nov. 3, 1959 – May 12, 1960
Frounze	74°37′ E	42°50′ N		Askania 126 & 134	Oct. 26, 1960 – May 1, 1961
Lantschou	103°51′ E	36°05′ N		Askania 124 & 135	June 21, 1959 – Aug. 21, 1959
Honolulu	157°49′ W	21°18′ N	29 m	LaCoste (2)	Oct. 14, 1956 – Nov. 22, 1956
Glendora	117°49′ W	34°10′ N	525 m	LaCoste (2)	May 28, 1957 – July 7, 1957
Wake	166°39′ E	19°18′ N	3 m	LaCoste (2)	July 27, 1957 – Sept. 5, 1957
Baguio	120°35′ E	16°25′ N	1525 m	LaCoste (1)	Aug. 14, 1957 – Oct. 31, 1957
Saigon	106°42′ E	10°47′ N	5 m	LaCoste (2)	Nov. 23, 1957 – Jan. 1, 1958
New Delhi	77°11′ E	28°38′ N	227 m	LaCoste (2)	Jan. 13, 1958 – Feb. 22, 1958
Los Angeles	118°26′ W	34°04′ N	131 m	LaCoste 4 & 6	Dec. 4, 1961 – Mar. 31, 1963

( ) shows a number of instruments.

its accurate value.

Observations in Central Asia were carried out by the Earth Physics Institute of the Soviet Academy of Sciences (Pariisky [1964]). Two Askania gravimeters were used in Alma Ata, Tashkent and Frounze. In Lantschou of China, observations were made by means of another two Askania gravimeters in collaboration with the Chinese Academy of Sciences during 2 months from June to August 1959.

On the other hand, observations in the Pacific Area were carried out by Harrison and others [1963] with two LaCoste Romberg tidal gravimeters. They made continuous observations for 30 to 40 days at each of 13 stations distributed around the world during a period of the International Geophysical Year. Among their 13 stations, 6 were situated on the Asian Continent or in the Pacific Area. Details of the observation stations and periods are shown in Table 1. Slichter and others [1964] carried out simultaneous observations with two LaCoste Romberg tidal gravimeters during a period more than 500 days at Los Angeles.

According to private communications to the present author, observations of the tidal variation of gravity are being made at other stations on the Asian Continent, but no analytical result concerned is available in the present case.

Data observed by the Askania gravimeters have been analyzed by an usual method of tidal analysis, and those by the LaCoste Romberg tidal gravimeters analyzed by the Fourier one. The author's investigation shows that no significant difference is recognized in analytical results between these two methods. Results of analysis obtained by the original authors will therefore be adopted in the following discussion, without taking the difference in methods of analysis into consideration.

Results of analysis are usually obtained for several major constituents. Among them, an amplitude of M_2-constituent (principal lunar semidiurnal constituent, with a speed of 28.984° per mean solar hour) is really in 90% of total lunar tides and is of the largest at a region of low latitudes near the equator. The M_2-constituent is not subject to thermal disturbances. The M_2-constituent is therefore considered to be highly trustworthy among the tidal constituents, especially for results derived from short-period observations such as one month. Consequently the succeeding discussion will be restricted to the M_2-constituent alone.

Values of the tidal factor of gravity G and phase lag κ for the M_2-constituent are shown in Table 2. The positive sign of κ shows that the observed tide advances the theoretical one, while the negative sign shows that the former lags behind the latter.

Table 2. Observational results

Observation station	$G(M_2)$	$\kappa(M_2)$
Japan (One month's observations)	1.139* ± 0.009	− 1.°91* ± 0.°79
Kyoto (One year's observation)	1.138* ± 0.005	− 2.40* ± 0.28
Chiba	1.141	+ 0.72
Alma Ata	1.135 ± 0.005	− 3.7 ± 0.4
Tashkent	1.137 ± 0.004	− 4.4 ± 0.2
Frounze	1.154 ± 0.003	− 3.6
Lantschou	1.143 ± 0.012	− 3.5 ± 0.8
Honolulu, Hawaiian Islands	1.190 ± 0.009	− 2.0 ± 0.49
Glendora, California	1.184 ± 0.013	+ 3.8 ± 0.65
Wake, Wake Island	1.174 ± 0.006	− 0.5 ± 0.35
Baguio, Manila	1.203 ± 0.003	+ 2.6 ± 0.13
Saigon	1.163 ± 0.005	+ 0.5 ± 0.22
New Delhi	1.153 ± 0.008	+ 1.6 ± 0.36
Los Angeles	1.164 ± 0.006	− 3.50 ± 0.90

* Corrected values.

4. Discussion

Values of the tidal factor of gravity G obtained by one month's observations at the Japanese stations are distributed to wide ranges from 1.11 to 1.24. But, generally speaking, the values of G obtained at stations near the Pacific Ocean are much larger than those at inland stations of Japan. Consequently, it is presumed that the values of G obtained at the coastal stations are disturbed by an effect of oceanic tides. Assuming then the effect of oceanic tides upon the tidal variation of gravity is tentatively expressed by a function with vertical component of attraction of the oceanic tides as a parameter, the tidal factor of gravity G in Japan free from influence of the oceanic tides can be determined. The value of G in Japan, shown in Table 2, is the corrected one thus obtained.

In a continuous observation at one place, it is unnecessary to take into account consideration the position of observation station, the effect caused by oceanic tides and the difference of local geological structure around the station. The value of G at Kyoto, shown in Table 2, is the corrected one free from influence of meteorological changes. Since the influence of oceanic tides is negligibly small at Kyoto, the G-value of Kyoto may be considered as the one free also from the oceanic tides. The values of Japan and Kyoto shown in Table 2 are, therefore, the most reliable values of G and κ in Japan, free from influences of the meteorological disturbances and oceanic tides.

The results obtained at Chiba, Alma Ata, Tashkent, Frounze and Lantschou are mean values of respectively several analyses, and those at Los Angeles are mean values of results obtained with two gravimeters.

As can easily be seen from Table 2, the value of G obtained at some stations in Asia is about 1.14 in common and that in the Pacific Area is somewhat larger than the value of Asia. Though the value of G in Japan is referred to as 1.14, which is the corrected value, original values obtained at the stations near the Pacific Ocean are distributed between 1.19 to 1.24.

On the other hand, the value of G obtained at the coastal stations near the Pacific Ocean or that on islands in the Pacific Ocean is distributed between 1.17 to 1.24 in compliance with distances from the Ocean. It is therefore presumed that the divergency in the values of G obtained in the Pacific Area is caused by the effect of oceanic tides. Theoretical values of the characteristic numbers have been calculated by Alsop and other [1964] for both continental and oceanic earth's models. Their results show that the value of G for the oceanic earth's model is somewhat larger than that for the continental one.

According to the recent observations made in the world (Melchior [1963]), the value of G obtained is about 1.19 at almost all of observation stations in Europe. Since a few observational results are merely available for other continents except Asia and Europe, it has not come to be established any definitive conclusion for their continents.

There is a distinct difference in the values of G between Asia and Europe. Such the difference between Asia and Europe is recognized not only in the tidal factor of gravity G but also in the phase lag κ. The value of κ is very small for both Asia and Europe, but its sign is opposite. That is, the observed tide lags behind the theoretical one in Asia, while the former advances the latter in Europe.

It seems very interesting and attracting to examine in detail whether this difference is real or apparent. The difference discovered between Asia and

Table 3. Systematic differences in results between Asia and Europe obtained by gravimetric tidal observations

		Asia	Europe
Tidal factor of gravity	$G(M_2)$	1.14	1.19
Phase lag	$\kappa(M_2)$	Negative	Positive
$G(M_2, S_2)-G(K_1, O_1)$		Negative	Positive
$G(O_1)-G(K_1)$		+ 0.02	+ 0.02

Europe is believed to be due to a regional heterogeneity in the elastic properties of the Upper Mantle, rather than to indirect effects.

Similar regional difference is also recognized in the following point. According to the theoretical investigations (Pekeris et al. [1959] and others), the tidal factor of gravity G for semidiurnal tides must be smaller than that for diurnal ones. The results obtained in Asia prove it. On the contrary, the G for semidiurnal tides is clearly larger than that for diurnal ones in Europe.

A difference between G-value of the lunar declinational diurnal constituent O_1 and that of the luni-solar declinational diurnal one K_1 obtained by gravimetric tidal observations is around +0.02 in both Asia and Europe. This difference is related to dynamic effects of the liquid core of the earth, as proposed by Molodensky [1961].

Tiltmetric tidal observations are being made at many stations in both Europe and Asia. According to observational results, values of D show a divergency of wide ranges in compliance with the position of observation stations, observation periods and components. As a tiltmetric observation is much disturbed by indirect effects than in a gravimetric one, it is natural presumed that the diminishing factor D obtained is disturbed by effects of oceanic tides, meteorological disturbances, geological structure and others. To discuss such the indirect effects upon the diminishing factor D is not the present purpose. The mean value of the diminishing factor D for M_2-constituent with a weight of analysis numbers is 0.72 in Europe.

In Asia, tiltmetric observations have been made at Ashkabad, Kondara, Alma Ata (Pariisky [1963]), Barim, several stations of Japan (Nishimura [1950]), many other ones of Japan and others. Tiltmetric observations in Japan are being made for a long time. Records obtained by the Japanese observations have been used for detecting any relation between a crustal deformation and seismic activities, and therefore the diminishing factor D has not yet been determined by using the data. Assuming then that the weighted mean value of the diminishing factor D obtained at the stations above mentioned is adopted as its definitive value in Asia, it is about 0.68.

Combining the value of G with that of D, the values of Love's numbers h and k are algebraically calculated.

$$h=0.68 \quad \text{and} \quad k=0.36 \quad \text{in Asia, and}$$

$$h=0.46 \quad \text{and} \quad k=0.18 \quad \text{in Europe.}$$

On the other hand, the value of k was obtained from Chandler's period to be 0.28 (Labrouste [1946]) and also from variations of the speed of the earth's rotation to be 0.29 (Markowitz [1959]). The value of k thus geophysically obtained is not agreeable with that of k obtained from astronomical observations.

Tidal observations with extensometers are being made at some stations in Japan during periods more than 10 years. According to the results obtained at Osakayama station, near Kyoto, by Ozawa [1965], the value of Shida's number l is very closed to 0.05. In Europe, tidal observations with extensometers have been made at Freiburg in West Germany by Hiersemann [1962] and also at other stations. Their results show that the value of l is nearly 0.07. Several stations equipped with Benioff's strainmeters have been established in California, Peru and Chile, but no numerical results of the earth tides appear to have been carried out.

By assuming that the values of l, obtained in Japan and Germany, are applicable for other places in Asia and Europe, respectively, and using the value of k above obtained, the value of L is calculated to be 1.31 in Asia and 1.11 in Europe.

As described above, the value of L can be derived from observations of latitude variations. According to the investigation by Sugawa [1964], the most reliable value of L derived from observations of latitude variations at Mizusawa in Japan is 1.30. The mean value of L determined from astronomical observations over the world is obtained to be 1.15 by Melchior [1959]. This value includes the Mizusawa's one. Therefore the value of L is slightly smaller than 1.15 in Europe. Assuming that the value of L obtained at Mizusawa is applicable for other places in Asia, the value of L obtained from astronomical observations is almost exactly agreement with that from geophysical ones for Asia and Europe, respectively.

As repeatedly mentioned above, the regional difference between Asia and Europe is clearly recognized in the values related with the earth tides. It could be due to a difference in constitutions of the Upper Mantle in the both continents.

Looking at circumstances about observations of the earth tides in the Pacific Area, no data are unfortunately available, in the present time, for investigating the earth tides except a limited number of stations in Japan and other countries. 8 and 5 observation stations have been established in Peru and Chile, respectively, by related Institutes under cooperative with the Kyoto University, in 1965. 2 sets of tiltmeters and those of extensometers were installed at each of the 13 stations. The main subject to be made in those stations is to examine a relation between crustal deformations and seismic activities. As the observational instruments are kept under an excellent condition and sufficient sensitivity, observational data will be available not only for researching the main purpose but also for investigating the earth tides. Almost all of observation stations of the earth tides in operation, are situated in a zone surrounded by latitudes of 10° to 60° in the Northern Hemisphere. Observations in Peru and Chile are much contributable in the geographical point of views.

Data obtained in Japan by means of tiltmeters and extensometers will be read and analyzed in near future. With an increase of the number of stations and of simultaneous observations, more detailed investigations will be made, and many other characteristic regional features may be discovered.

If the earth were perfectly incompressible, homogeneous and being uniform rigidity, it should be calculated

$$\mu = 9.73 \times 10^{11} \text{ dyne/cm}^2 \quad \text{in Asia, and}$$
$$\mu = 1.61 \times 10^{12} \text{ dyne/cm}^2 \quad \text{in Europe.}$$

Using the value of h obtained above, the greatest tidal ascent and descent of the ground that could occur on the earth is calculated as

$$U = 53.0 \text{ cm} \quad \text{in Asia, and}$$
$$U = 35.9 \text{ cm} \quad \text{in Europe.}$$

A thorough investigation for the cause of regional differences discovered between Asia and Europe, is an important and interesting problem. Continuous and simultaneous observations on the earth tides should be strongly required by means of various instruments, for periods as long as possible, at many stations over the world.

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