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The Observations of the Earth Tidal Strains in Old Osakayama Tunnel

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Abstract

Observatons of the earth tidal extensions have been performed with newly improved highly sensitive extensometers in the old Osakayama tunnel. The influences on the observed extensions caused by the atmospheric tide and the existence of the tunnel have been studied theoretically and experimentally. According to the study of our observations, these atmospheric and hole effects are large in the orthogonal direction to the tunnel.

From these studies the revised values of the tidal factors of the vertical, the areal and the dilatational strains have been obtained.

1. Introduction

The observations on the earth tide are broadly divisible into the micscopic class and the macroscopic one. The former observation methods have obtained the tidal variation of the minute parts of the earth which are chiefly something of the derivative functions of the tidal displacement. These observations have been performed by use of the tiltmeter, extensometer, rotationmeter, theodolite and so on. These results have been compared with the theoretical values which have been obtained by the derivative of the earth tidal displacement respect to the earth's spatial coordinate. The observation of the tide on the ocean or large lakes belong to the macroscopic class. The adaptability of the observations of the tide gauge are not so good as the results of the former class for the analyses of the tidal deformation of the earth. However, another method which is called VLBI (very long baseline interferometry) has been developed recently. This is applicable to the macroscopic observation, but the sensitivity of the VLBI[1] has reached a few centimeters on a baseline which is longer than 1 000 km, and it may bear comparison with the sensitivity of the extensometer.

In this state of art, we should reexamine the accuracy of the observations of the microscopic class. So far, observations by use of tiltmeters, extensometers, and other instruments have been performed in the room under the ground where are tunnel or the gallery in order to avoid the effects of the weather which include the variations of atmospheric pressure, the room and ground temperature, precipitation and so on.

But usually the boundary conditions of the observing room under the ground surface are complex. Therefore, the theoretical studies of the stress field of underground rooms have been performed by some researchers, for example, Hiramatsu and Oka[2] (1962), Ozawa (1973)[3], Harrison[4] (1976), Takemmoto[5] (1982) and so on. Hence, this author has reexamined the effect of the boundary conditions in the observing room in the old Osakayama tunnel, and will produce these observational studies in this paper.

2. Basic theory

The tidal deformation of the earth (body tide) approximates usually to the spheroidal type. So, the components of the tidal displacement, u_r, u_θ and u_ϕ are given in the polar coordinate (r, θ, ϕ) whose origin is at the center of the earth are given as follows,

$$u_r=\frac{h}{g}W_2,\quad u_\theta=\frac{l}{g}\frac{\partial W_2}{\partial\theta},\quad u_\phi=\frac{l}{g\sin\theta}\frac{\partial W_2}{\partial\phi},\qquad \cdots\cdots\cdots\cdots (1)$$

where r, θ and ϕ are the radius, the co-latitude and the longitudinal vectors, respectively. h and l are Love's and Shida's tidal numbers, respectively. g is the mean value of the the gravity acceleration on the earth's surface which is used as a conventional number for the numerical calculation. W_2 is the potential of the tide generating force which is the product of the constant, r^2 and the spherical harmonic function of the second degrees, $S_2(\theta, \phi)$. We obtain the strain components using the relation between the strain and the displacement shown as equation (1) as follows[6],

$$e_{rr}=\left(r\frac{\partial h}{\partial r}+2h\right)\frac{\partial W_2}{rg},\qquad e_{\theta\theta}=\frac{1}{rg}\left(hW_2+l\frac{\partial^2 W_2}{\partial\theta^2}\right),$$

$$e_{\phi\phi}=\frac{1}{rg}\left(hW_2+\frac{l}{\sin^2\theta}\frac{\partial^2 W_2}{\partial\phi^2}+l\cot\theta\frac{\partial W_2}{\partial\theta}\right),$$

$$e_{\theta\phi}=\frac{2}{rg}\frac{l}{\sin\theta}\left(\frac{\partial^2 W_2}{\partial\theta\partial\phi}-\cot\theta\frac{\partial W_2}{\partial\phi}\right),$$

$$e_{r\theta}=\frac{1}{rg}\left(h+r\frac{\partial l}{\partial r}+l\right)\frac{\partial W_2}{\partial\theta}\qquad e_{r\phi}=\frac{1}{rg\sin\theta}\left(h+r\frac{\partial l}{\partial r}+l\right)\frac{\partial W_2}{\partial\phi},$$

$$\Sigma=e_{\theta\theta}+e_{\phi\phi}=2(h-3l)\frac{W_2}{rg},$$

$$\Delta=e_{rr}+e_{\theta\theta}+e_{\phi\phi}=\left(r\frac{\partial h}{\partial r}+4h-6l\right)\frac{W_2}{rg}.\qquad \cdots\cdots\cdots\cdots (2)$$

In order to satisfy the boundary condition of the free surface at the earth's surface, it needs

$$e_{r\theta}=e_{r\phi}=0.$$

According to the relations between the stress and strain components, we obtain the following relations,

$$\sigma_r=\lambda\Delta+\frac{2\mu}{rg}\left(r\frac{\partial h}{\partial r}+2h\right)W_2,\qquad \sigma_\theta=\lambda\Delta+\frac{2\mu}{rg}\left(hW_2+l\frac{\partial^2 W_2}{\partial\theta^2}\right),$$

$$\sigma_\phi=\lambda\Delta+\frac{2\mu}{rg}\left(hW_2+\frac{l}{\sin^2\theta}\frac{\partial^2 W_2}{\partial\phi^2}+l\cot\theta\frac{\partial W_2}{\partial\theta}\right)$$

$$\tau_{\theta\phi}=\frac{2\mu l}{rg\sin\theta}\left(\frac{\partial^2 W_2}{\partial\theta\partial\phi}-\cot\theta\frac{\partial W_2}{\partial\phi}\right),$$

$$\tau_{r\theta}=\frac{\mu}{rg}\left(h+r\frac{\partial l}{\partial r}+l\right)\frac{\partial W_2}{\partial\theta},\qquad \tau_{r\phi}=\frac{\mu}{rg\sin\theta}\left(h+r\frac{\partial l}{\partial r}+l\right)\frac{\partial W_2}{\partial\phi}\qquad \cdots\cdots\cdots\cdots (3)$$

where λ and μ are the elastic coefficients of Lamé. We have also the relations

$$\sigma_r=\tau_{r\theta}=\tau_{r\phi}=0,$$

at the earth's suface $r=a$.

The components of the tidal strain are influenced geneally by loading of the oceanic tide. These effects have been precisely explained by this author[7] and many researchers. The effects of the oceanic tide for the vertical and the dilatational strains may be neglected at Osakayama, because the observatory is at a far distance from the ocean, and it may be assumed the earth's surface is almost horizontal.

The topographical effect of the crust may be also neglected here, because the effect is smaller than few percents of the primary body tide. The problem of these two effects is interesting for the geophysical and mechanical researches. But, it is more impotant and more urgent to study the cavity and atmospheric pressure effects on the observatory in order to obtain the reliable observed values of the earth tide.

We will consider the stress field around the observing tunnel and the resultant strain due to the stress field. Many books of the elastic theory explain a stress field around a circular hole in a plate. Hiramatsu and Oka (1962) have studied the pattern of the resultant strains on the walls of the various type tunnel shape by the photoelasticity experiments. Recently, the calculations of the stress field have been practised by use of the finite element method by many researchers. The studies of the tidal stress and the strain around the tunnel are given in this paper.

The stress field caused by W_2 can be expressed in the three terms of the principal stress, σ_r, σ_θ and σ_ϕ at far distance from the tunnel. Therefore, the vertical strain, e_{rr}, is expressed as

$$e_{rr}=\frac{1}{E}\left\{\sigma_r-\nu(\sigma_\theta+\sigma_\phi)\right\},\qquad \cdots\cdots\cdots\cdots (4)$$

where E and ν are the Young's modulus and the Poisson's ratio, respectively. As the depth of the observing site is much smaller than the radius of the earth, we may neglect the radius component of the normal stress, σ_r, in this problem. Therefore, the normal stresses σ and σ' in the direction of $\psi+\pi/2$ and in that of ψ are given at far distance from the tunnel as follows,

$$\sigma=\sigma_\theta\sin^2\psi+\sigma_\phi\cos^2\psi,$$

$$\sigma'=\sigma_\theta\cos^2\psi+\sigma_\phi\sin^2\psi.\qquad \cdots\cdots\cdots\cdots (5\text{–}1)$$

and the shear stress, τ, on the horizontal plan is given as follows,

$$\tau=(\sigma_\phi-\sigma_\theta)\sin\psi\cos\psi. \qquad \cdots\cdots\cdots\cdots \quad (5\text{–}2)$$

We are able to estimate that the normal stresses σ and σ' are uniform in this problem. And the shear stress, τ, is able to be substituted with two normal stresses. Since length of this tunnel is much longer than its radius, a_1, therefore, we can treate this stress field around the tunnel as a two dimensional problem.

We take two dimensional polar coordinate (R, θ_1) orthogonal to the axis of the tunnel shown as **Fig. 1**. The origin of the coordinate is put at the center of the transversal section of the tunnel. To simplify the solution of the problem, the section is assumed to be a circle. The normal stress in the direction of the axis of the tunnel can be treated as an additional term for the two dimensional problem. We may consider that the only one normal stress, σ_1, is applied in the x-direction at far distance from the tunnel hole in this problem.

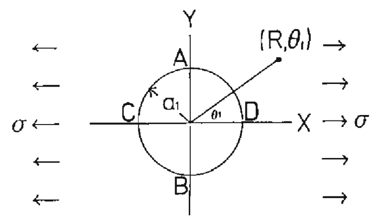

Fig. 1 Schematic diagram of the stress field around the circular hole in the plate

The radius, R, and transverse, θ_1, components of the displacement u_R and $u_{\theta 1}$ around the hole are given as follows[8],

$$u_R=\frac{\sigma_1}{8\mu R}\left\{(\kappa-1)R^2+2a_1{}^2+2\left[a_1{}^2(\kappa+1)+R^2-\frac{a_4^1}{R^2}\right]\cos 2\theta_1,\right.$$

$$u_{\theta 1}=-\frac{\sigma_1}{8\mu R}\left\{R^2+a_1^2(\kappa-1)+\frac{a_1^4}{R^2}\right\}\sin 2\theta_1,$$

$$\kappa=3-4\nu. \qquad \cdots\cdots\cdots\cdots \quad (6)$$

From the equation (6), the mean extension, E_v of the vertical radius $\overline{AB}$ by the tension, σ_1, is obtained as,

$$E_v=-\frac{\sigma_1}{2\mu}(1-\nu)\doteqdot-0.375\frac{\sigma_1}{\mu}. \qquad \cdots\cdots\cdots\cdots \quad (7)$$

Similarly, the mean extension, E_H, of the horizontal radius $\overline{CD}$ is obtained as follows,

$$E_H\doteqdot\frac{15\sigma_1}{8\mu}=1.875\frac{\sigma_1}{\mu}. \qquad \cdots\cdots\cdots\cdots \quad (8)$$

Fig. 2 shows the schematic diagram of the setting of the extensometer, V5.

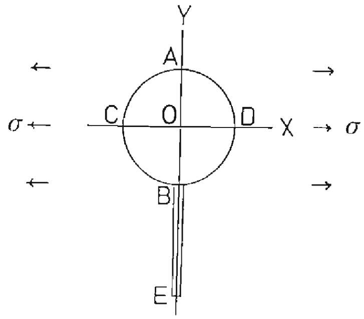

Fig. 2 Schematic diagram of the installation of the vertical component of the extension V5

Similarly, the mean extension, E_w, of the well $\overline{BE}$ caused by the tension, is obtained from the equation (6) as follows,

$$E_w = \frac{\sigma_1}{8\overline{BE}\mu}\left\{\frac{1}{a_1+\overline{BE}}\left[(a_1+\overline{BE})^2(\kappa-3)-2\kappa a_1^2+\frac{2a_1^4}{(a_1+\overline{BE})^2}\right]+a_1(\kappa+1)\right\}. \quad \cdots\cdots\cdots\cdots (9)$$

If it be $\overline{BE}=3a_1$, the mean extension, E_w, is obtained as,

$$E_w = \frac{\sigma_1}{4\mu}\left(\frac{27}{64}-3\nu\right) \doteqdot -0.08203\frac{\sigma_1}{\mu}. \quad \cdots\cdots\cdots\cdots (10)$$

The strain components e_{xx} and e_{yy} caused by the tension, σ_1, are σ_1/E and $-\nu\sigma_1/E$ at the far distnace from the tunnel, respectively. According to the equations (7), (8) and (10). Therefore, these mean extensions E_v, E_H and E_w are $1.875E/\mu$ times, $0.375E/\nu\mu \doteqdot 1.5E/\mu$ times and $0.1641E/\nu\mu \doteqdot 0.6562E/\mu$ times of those at the far distance from the tunnel, respectively. Since the value of E/μ of the perfect elastic materials is 2.5, these values are nearly equal to 4.69 times, 3.75 times and 1.64 times, respectively.

But, these hole effects seem to be smaller in the actual situation except vertical component because the floor of the tunnel is flat like the ground surface. According to the study by Hiramatsu and Oka[2], the stress coefficient on the wall of the rectangular hole is nearly equal to that of the flat ground at a quarter of the side distance from the corner of the hole.

This gives very advantageous circumstances that in the radius direction of a tunnel we can observe the tidal extension without an extremely sensitive instrument. This fact might have helped the development in the study of the observations of the earth tide.

3. Observations

The highly sensitive extensometers[9] have been improved and the observations of the earth tidal extensions have been performed in the old Osakayama tunnel of the old Tokaido line[10]. The observing site is located at 34° 59′ N. and 135° 54′ E.. The basements of the observation is as deep as 60 meters under the ground surface.

Fig. 3 shows the locations of the observing instruments which are described in this paper. The extensometers, L3 and L2 have been set parallel to the axis of the main tunnel azimuth of which is S 38° W. The extensometer C1-old had been set over and orthogonal to the two main tunnels. And the observing direction is S 52° E. At first, the one end of the base line of the C1-old was on the wall-foot (corner) of the tunnel as shown in **Fig. 4(a)**. Afterward, the end of the C1-new has been separated

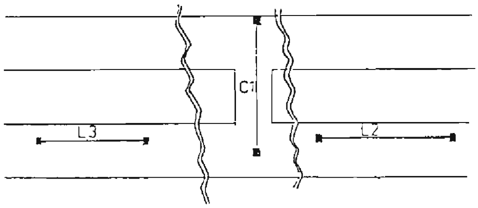

Fig. 3 The locations of the horizontal components of the extensometers in the tunnel

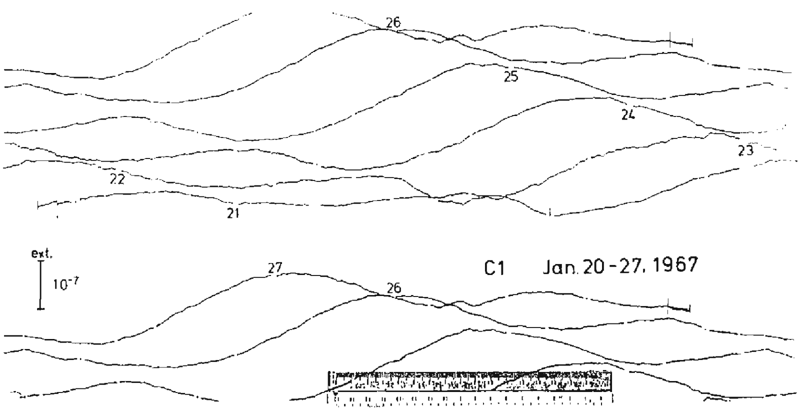

Photo 1(a) The photographic record of the extensometer C1-old in S 52°E

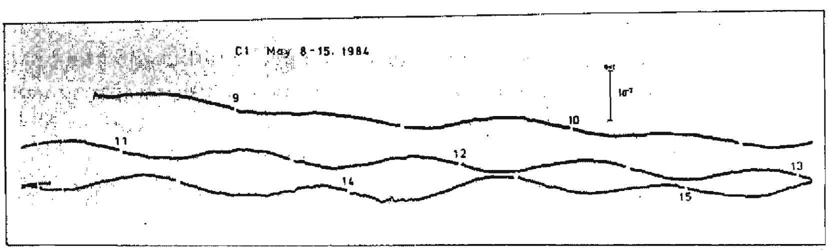

Photo 1(b) The photographic record of the extensometer C1-new in S 52°E. The amplitude of the tidal change of the C1-new is much smaller than that of the C1-old.

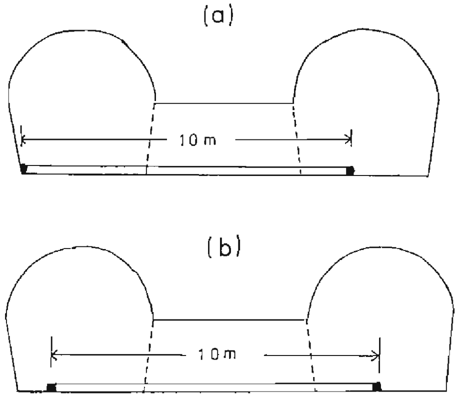

Fig. 4 The schematic diagram of the installations of the extensometers in S 52°E. (a) is the C1-old, and (b) is the C1-new.

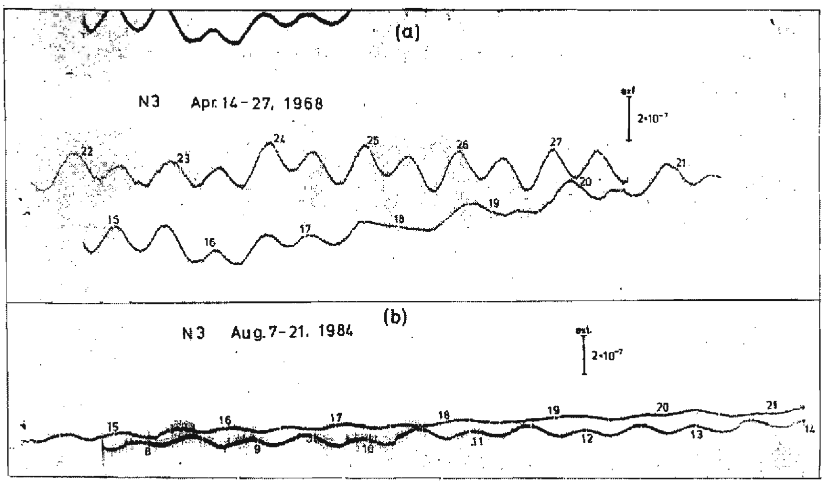

Photo 2 The photographic records of the extensometers N3 in the north. (a) is the record of the N3-old. (b) is the record of the N3-new. The amplitude of the tidal change on the N3-new is much smaller than that on the N3-old.

from the wall-foot, and has been set on the floor at 1 m distnace from the wall in 1976.

N3-old extensometer has been set in the direction of the north as shown in **Fig. 5(a)** in 1960. The end of the base line of the N3-old was on the wall-foot of the tunnel. Afterward, N3-new has been reset, and the one end is at 79 centimeters distnace from the wall as shown in **Fig. 5(b)**.

The amplitudes of the recording tidal variations on the extensometers C1 and N3 have decreased after their resettings.

The vertical components of the extensometers, V1, V3 and V5 have been set as shown in **Fig. 6(a)**, **(b)** and **(c)**.

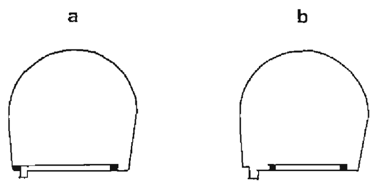

Fig. 5 The schematic diagram of the installations of N component extension. (a) is the extensometer N3-old, (b) is the extensometer N3-new.

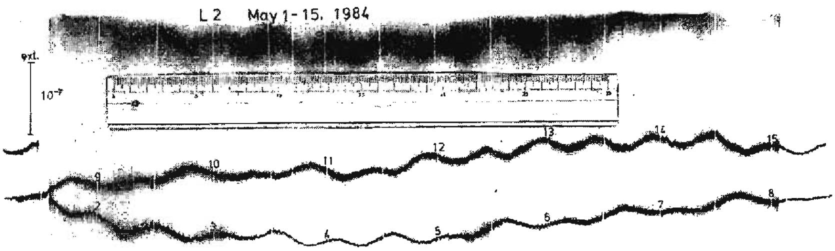

Photo 3 The photographic record of the extensometer L2 in S 38°W

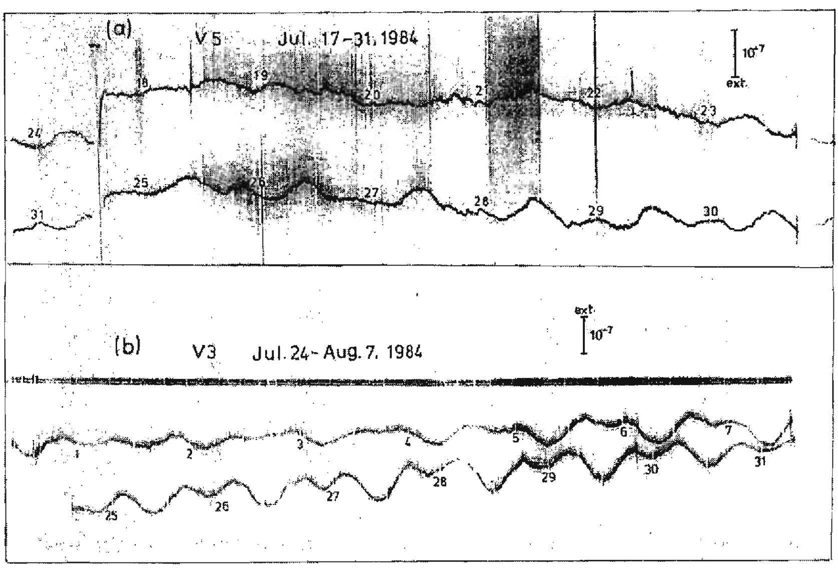

Photo 4(a) and (b) The photographic records of the vertical extension. (a) and (b) are the records of the extensometers V5 and V3, respectively. The amplitude of the tidal change of the V3 is much larger than that of the V5.

4. Method of analysis

The non-taidal variations on the observed curves have been eliminated by use of digital filters during the first process of the analysis. The digital filter whose

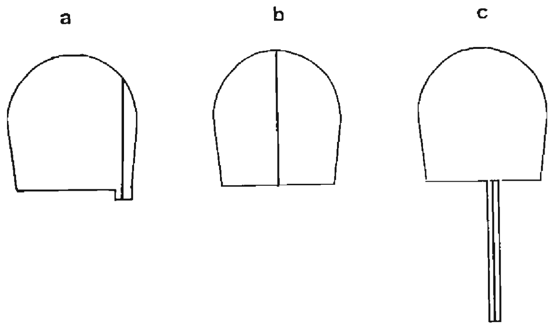

Fig. 6 The schematic diagrams of the installations of the extensometers, V1, V3 andV5. (a), (b) and (c) show the installations of the V1, V3 and V5, respectively.

window width is about 25 hours and whose weight is unity has been used before 1977. Recently, we use the window filter as follows,

$$Y(t)=X(t)-\sum_{n=-12}^{12}\{13-\mathrm{abs}(n)\}X(t+n)/169, \qquad \cdots\cdots\cdots\cdots \quad (11)$$

where $X(t)$, $Y(t)$, abs(n), t and n are the hourly values of the observed records of the extensometer, the filtered tidal variation, the absolute value of n, the number of the hours and integral numbers, respectively.

The tidal components have been analysed by the improved Darwin's method before 1977. Afterward, we have used the method of the calculations of the Fourier coefficients. The relations of the numbers of the hours which are used for the analysis and its analysed values are shown in **Fig. 7**. **Fig. 7(a)** shows the analysed amplitude and the phase angle of M_2-tide component versus the number of the hours used for the analysis of L2 extension. **Fig. 7(b)** and **(c)** show the relations between those on O_1 and S_2 components of the L2 extension.

According to this observed result, the amplitude and phase angle of the tidal change with the number of the hour used for the analysis. And the change of those of the observed tide is larger than that of the analysis of the purely predicting tide curve. For example, the scattering of the analysed amplitude and the phase angle are 1.8% and 2 degrees, respectively on the M_2-tide analysis for the period from 2800 hours to 2900 hours on the L2 extension. The scatterings of those of S_2-tide are larger than those of the M_2-tide, and they amount to 3% and 5 degrees. But those scatterings of the theoretically synthesized tide curve for an analysed period of only 1440 hours are within 0.1% and 1 degree only.

It seems that the observed extensions have many non-tidal variations of which periods are near those of the tidal components. And it seems that the larger the tidal stress in the crust becomes, the smaller the apparent elastic moduli of the ground become. We often see the phenomenon that the observed tidal change is very large in the full or new moon, but the amplitude in the half moon is much smaller than its predicting amplitude. This phenomenon can not be interpreated perfectly by the

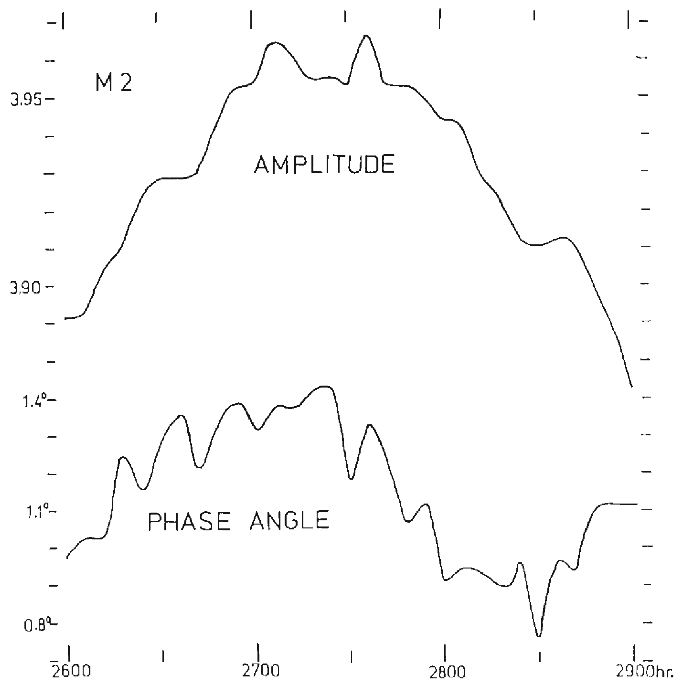

Fig. 7(a) The relation between the amplitude and phase angle versus the number of the hours of the period of the tidal analysis of the M_2-tide on the extension L2 for Dec., 1983—Apr., 1984

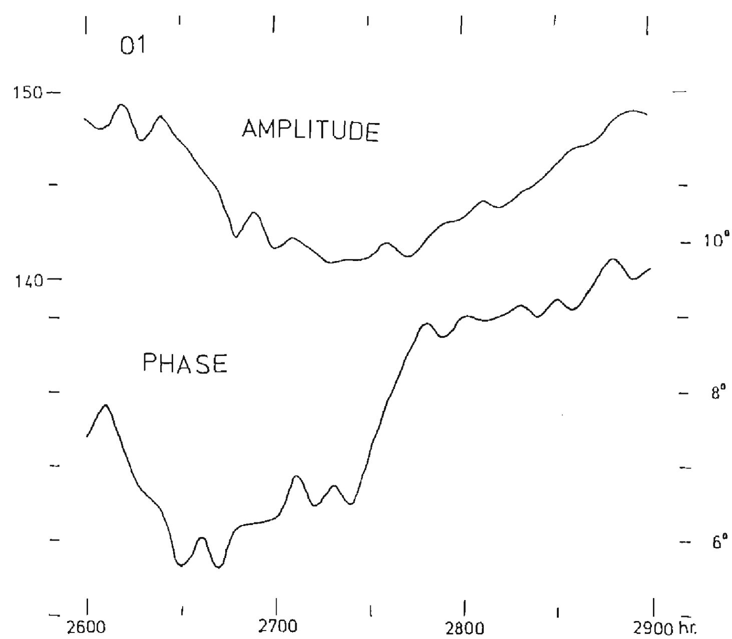

Fig. 7(b) The relation between the amplitude and the phase angle versus the number of the hours of the period of the tidal analysis of the O_1-tide on the extension L2 for Dec., 1983—Apr., 1984

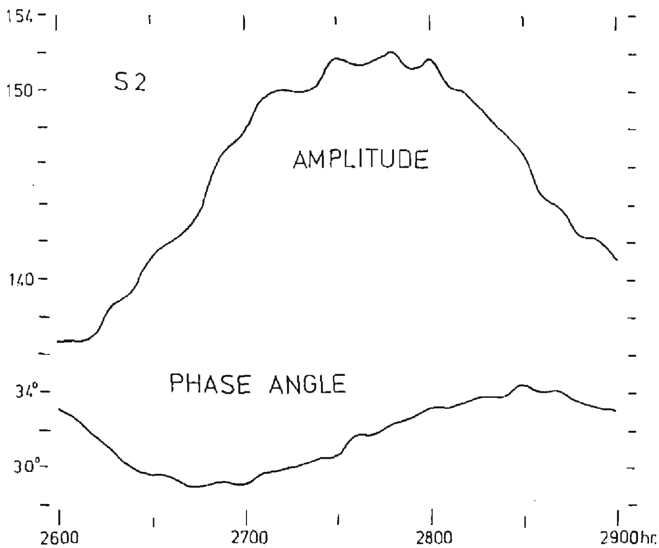

Fig. 7(c) The relation between the amplitude and the phase angle versus the number of the hours of the period on the tidal analysis of the S_2-tide on the extension L2 for Dec., 1983—Apr., 1984

ratio of the signal to noise only.

Fig. 8(a), (**b**), (**c**) and (**d**) show the relations between the analysed amplitude and the phase angle versus the periodic speed on the L2 extension (S 38° W) and V5 extension (vertical). We find some peaks of the amplitude around the periods of the main components, S_2, M_2, K_1 and O_1 in the **Fig. 8**. The phase angle of these peaks fluctuate rapidly between $-180°$ and $+180°$. And we find the small peaks in the both side of the main peaks of S_2, M_2, K_1, S_1 and O_1. These rapid phase changes and the appearance of these small peaks seem to be the character of the Fourier coefficients which are calculated by the integrations in the interval of the finite length.

5. Effect of the atmospheric tide

According to the results in the foregoing chapter, the analysed value of S_2-tide considerably differs from those of the analysed M_2-tide in generally. It seems to be one of the reason why the analysed period of the curve is not sufficiently long. A more important reason seems to be the effect of the pressure due to the atmospheric tide whose period is 12.00 hours. Now, we put the apparent analysed value of the S_2-tide to be S_{20}, and which is as follows,

$$S_{20}=S_2+S_{2,a},$$
$$S_2=M_2\times(S_{2,t}/M_{2,t}),$$
$$S_{2,t}/M_{2,t}=0.46531. \qquad \cdots\cdots\cdots\cdots \quad (12)$$

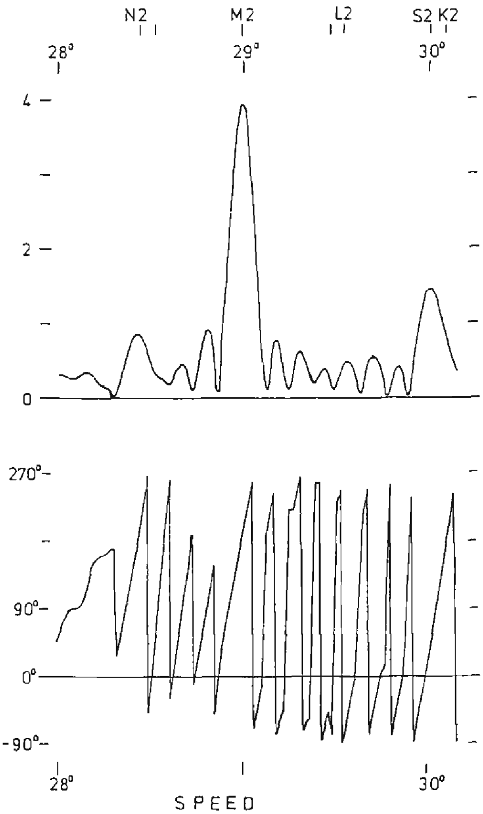

Fig. 8(a) The relation between the analysed amplitude and the phase angle versus the periodic speed in the Fourier analysis on the extensional component, L2 (S 38°W) for Dec., 1983—Apr., 1984

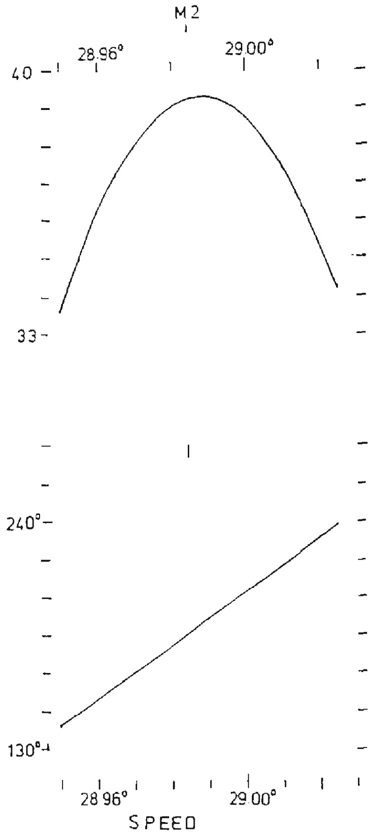

Fig. 8(b) The relation between the analysed amplitude and the phase angle versus the periodic speed whose region is around 29° in the Fourier analysis on the extensional component, L2 (S 38° W)

where S_2 is the pure value of the S_2-tide, M_2 is the analysed value of the M_2-tide, S_{2},t and M_{2},t are the ratios of the theoretical coefficients of S_2 and M_2-tides, respectively. S_{2},a is the effect caused by the atmospheric tide. Using this assumption (12), we obtained the values of S_{2},t and S_{2},a as in **Table II**.

According to these results, the extensional effects caused by the atmospheric pressure in the orthogonal and the vertical directions of the tunnel are larger than that in the direction of the tunnel. And these effective extensions on the C1-old and the N3-old are much larger than those of the C1-new and N3-new. The pressure of the atmospheric tide deforms the section of the tunnel. The extensional effect consists of the that of the global pattern of the atmospheric tide and that of the hole effect caused by the atmospheric pressure in the tunnel.

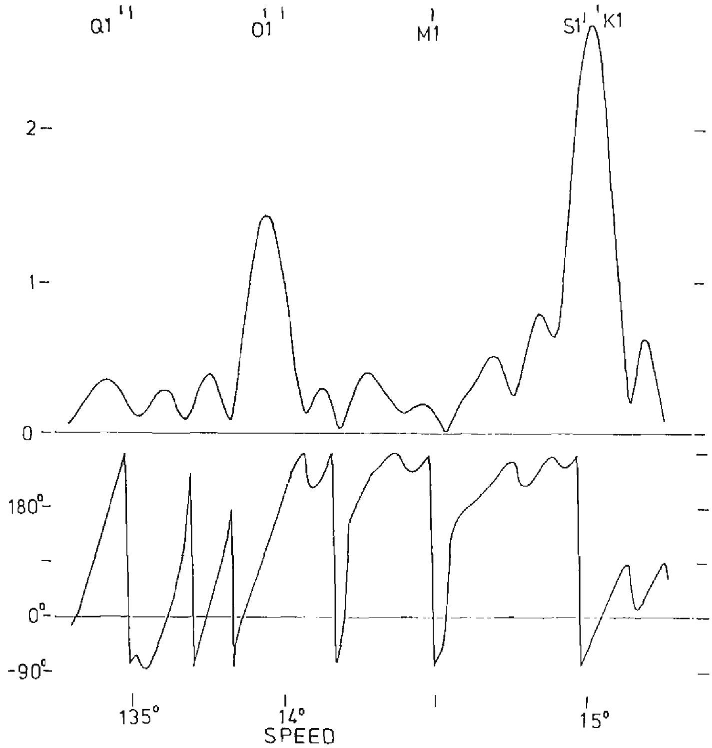

Fig. 8(c) The relation between the analysed amplitude and the phase angle versus the periodic speed whose region is around 29° in the Fourier analysis on the extensional component, L2 (S 38°W)

The amplitude of the atmospheric tide is about 1 millibar $=10^3$ dyn/cm^2 at Osakayama. We assume that a cylindrical hole is in a infinite elastic body, and the Young's modulus is 2×10^{11} c.g.s., the effective extension of hole effect is calculated as -8.125×10^{-8} for the radius direction, and is -0.050×10^{-8} in the direction of the tunnel.

According to Haurwitz[11] et al. (1957), the empirical expression for the S_2-component of the atmospheric tide S_{OB} has been given as follows.

$$S_{OB}(\theta)=1.23\{\bar{P}_2^2(\theta)-0.182\ \bar{P}_4^2(\theta)\}\ \sin\ (2T'+2\phi+158°)\ \text{mb.} \qquad \cdots\cdots\cdots\cdots \quad (15)$$

where $\bar{P}_n^m$ is the Schmidt's semi-normalized assosiated Legendre function of degree n and order m, and T' is the Greenwich standard time. The global strain components due to the atmospheric pressure which is given by (15) are obtained by use of the load tidal numbers[12], h' and l' as follows[13],

$$e'_{\theta\theta}=\left\{\frac{r^2A_2}{a^3g}\left[2l'_2\cos2\theta+\frac{1}{2}h'_2(1-\cos2\theta)\right]+\frac{r^4A_4}{a^5g}\left[2l'_4\left(\cos4\theta-\frac{1}{7}\cos2\theta\right)+\right.\right.$$

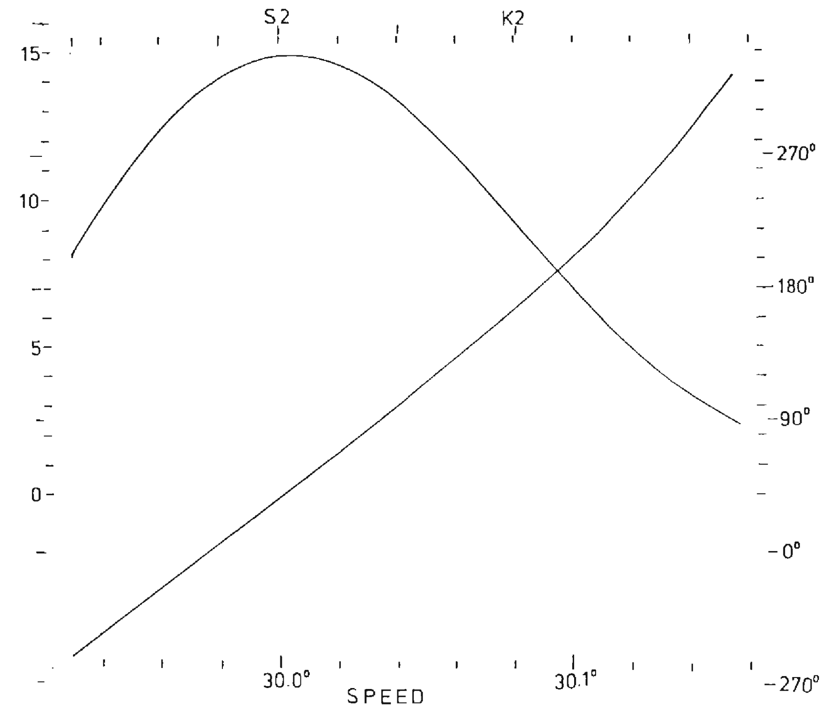

Fig. 8(d) The relation between the analysed amplitude and the phase angle versus the periodic speed whose region is around 30° in the Fourier analysis on the extensional component, L2 (S 38°W)

$$+\frac{h_4'}{56}(3+4\cos 2\theta-7\cos 4\theta)\Big]\Big\}\cos 2(T'+\phi+\varepsilon),$$

$$e_{\phi\phi}'=\left\{\frac{r^2A_2}{a^3g}\left[l_2'(\cos 2\theta-3)+\frac{1}{2}h_2'(1-\cos 2\theta)\right]+\frac{r^4A_4}{a^5g}\left[\frac{l_4'}{14}(7\cos 4\theta-16\cos 2\theta-15)+\right.\right.$$

$$+\frac{h_4'}{56}(3+4\cos 2\theta-7\cos 4\theta)\Big]\Big\}\cos 2(T'+\phi+\varepsilon),$$

$$e_{\theta\phi}'=\left\{\frac{r^2A_2}{a^3g}(-4l_2'\cos\theta)+\frac{r^4A_4}{a^5g}l_4'\frac{1}{2}(7\cos 3\theta-\cos\theta)\right\}\sin 2(T'+\phi+\varepsilon),$$

$$e_{rr}'=\left\{\frac{A_2r^2}{a^3g}\left(r\frac{\partial h_2'}{\partial r}+2h_2'\right)\bar{P}_2^{\,2}(\theta)+\frac{A_4r^4}{a^5g}\left(r\frac{\partial h_4'}{\partial r}+4h_4'\right)\bar{P}_4^{\,2}(\theta)\right\}\sin 2(T'+\phi-\varepsilon),$$

$A_2=1.235$ mb, $A_4=-0.224$ mb, $\varepsilon=79°$. .... (16)

According to Longman (1963)[12], $h_2'=-1.007$, $l_2'=0.030$, $h_4'=-1.059$, $l_4'=0.062$[12]. Ozawa (1967)[13] has obtained the numerical values of the strain components due to the atmospheric tide by use of the assumption of $a\partial h'/\partial r=(1-n)h_n'$ at old Osakayam tunnel as follows,

$$e_{\theta\theta}'=0.0206\times 10^{-8}\cos(2t-249.8°),$$
$$e_{\phi\phi}'=0.1619\times 10^{-8}\cos(2t-249.8°),$$

Table I Analysed constant of the tidal extension

Component of extension	Sign of instrument	Epoch of analysis	Number of analysed month	M_2-tide Amplitude $\times 10^8$	Phase	O_1-tide Amplitude $\times 10^8$	Phase	Method of analysis
Vertical	V1	'52:12:25	1	0.44	215°			Improved Darwin
〃	〃	'53: 3:12	1	0.63	201			
〃	〃	'54: 3:12	1	0.64	193	0.61	232°	〃
〃	〃	'54:10: 7	1	0.74	174			〃
〃	〃	'54:11: 5	1	0.84	192			〃
〃	V3	'60: 1: 1	3	2.795	180.9	1.396	176.4	Fourier coefficient
〃	V5	'64: 8:12	1	0.510	198.3	0.757	202.6	Improved Darwin
〃	〃	'64: 9:16	1	0.525	198.4	0.582	219.2	〃
〃	〃	'81: 1: 1	3	0.480	174.5	0.402	169.4	Fourier coefficient
S 38°W	L3	'60: 8:25	9	0.457	13.4	0.231	335.6	Improved Darwin
〃	L2	'65: 9:24	2	0.354	11.2	0.294	30.4	〃
〃	〃	'83:12:27	4	0.562	13.70	0.244	325.46	Fourier coefficient
S 52°E	Cl-old	'60: 9:30	9	1.537	353.5	0.775	8.5	Improved Darwin
〃	〃	'61:11: 5	4.5	1.433	359.1	1.104	13.5	〃
〃	Cl-new	'79: 8: 1	3	0.618	331.2	0.321	12.7	Fourier coefficient
〃	〃	'83:12: 7	1	0.706	5.4	0.307	13.29	〃
N	N3-old	'79:10:31	1	2.129	9.53	0.618	6.86	〃
〃	N3-new	'84: 1: 1	1	1.064	12.70	0.354	352.28	〃
〃	N1	'59: 4:23	3	1.362	10.9	0.640	20.8	Improved Darwin
E	E1	'59: 5:24	3	0.880	357.8	0.760	3.5	〃

Table II The extensional effect caused by the pressure of the atmospheric tide on the S_2-tide component

No.	Sign of Instrument	Analysed S_2-tide (S_2, o) Amplitude $\times 10^8$	Phase	Theoretical S_2 (S_2, t) Amplitude $\times 10^8$	Phase	Effect of Atmospheric tide (S_2, a) Amplitude $\times 10^8$	Phase
1	Cl-old	0.755	310.4°	0.717	353.5°	0.513	244.2°
2	Cl-new (1979)	0.387	279.7°	0.288	331.2°	0.306	232.5°
3	Cl-new (1984)	0.133	302.8°	0.329	5.4°	0.293	240.8°
4	L2	0.140	34.4°	0.262	13.7°	0.140	173.0°
5	N3-old	1.295	319.4°	0.993	9.5°	1.007	270.2°
6	N3-new	0.509	333.2°	0.496	12.7°	0.340	265.0°
7	V3	1.628	161.5°	1.304	180.9°	0.240	181.2°
8	V5	0.163	199.5°	0.227	190.8°	0.074	351.5°

$$e'_{\theta\phi}=0.0022\times10^{-8}\cos(2t-110.2°),$$
$$e'_{rr}=0.0961\times10^{-8}\cos(2t-249.8°),$$
$$e'_{S38°W}=0.0951\times10^{-8}\cos(2t-230.8°),$$
$$e'_{S52°E}=0.1479\times10^{-8}\cos(2t-230.8°),\quad t=T'+\phi \qquad \cdots\cdots\cdots\cdots (17)$$

According to the value of **Table II** and the results (17), we have the extensional effect due to the atmospheric pressure in the tunnel on the S_2-tide as follows,

$0.371 \times 10^{-8} \cos(2t-249.51°)$ on the C1-old,
$0.146 \times 10^{-8} \cos(2t-240.90°)$ on the C1-new,
$0.988 \times 10^{-8} \cos(2t-270.62°)$ on the N3-old,
$0.320 \times 10^{-8} \cos(2t-265.97°)$ on the N3-new,
$0.120 \times 10^{-8} \cos(2t-142.95°)$ on the L2,
$0.224 \times 10^{-8} \cos(2t-157.61°)$ on the V3,
$0.133 \times 10^{-8} \cos(2t-36.69°)$ on the V5. .... (18)

6. Hole effect of the tunnel

The hole effect of the simple structure (circular hole) has been estimated in the foregoing chapter. The observed results of our observations are as follows. The analysed tide components observed with the instruments whose ends of the baseline are on the wall have much been effected by the hole. The difference between the observed value of the extensometer whose end of the baseline is on the wall and that of the extensometer whose end is kept away from the wall is obtained as follows. The difference between the tide components of the C1-old and C1-new are as follows,

$0.9069 \times 10^{-8} \cos(2t-356.30°)$ on the M2-tide,
$0.4626 \times 10^{-8} \cos(t-5.46°)$ on the O1-tide,
$0.5139 \times 10^{-8} \cos(2t-324.81°)$ on the S2-tide. .... (19)

The difference between the component tide of the V3 (in 1960) and that of the V5 (in 1979) are as follows,

$2.3085 \times 10^{-8} \cos(2t-178.79°)$ on the M_2-tide,
$0.9225 \times 10^{-8} \cos(t-162.16°)$ on the O_1-tide,
$1.2839 \times 10^{-8} \cos(2t-158.91°)$ on the S_2-tide.

According to these results, we recognize that the hole effect is not negligible especially in S_2-component. However, it seems that the hole effect is able to be eliminated effectively.

7. Tidal factor of the vertical, the areal and the dilatational strains

We find that the observations have much been effected due to the hole boundary of the tunnel. However, we may presume that the observations along the direction of the tunnel, L2, L3, C1-new and that in the well (V5) are free from the effect of the hole.

Hence, we have the tidal strain factor on the vertical extension by the analysed value of the V5 by use of the formula (2) as follows,

$$a\frac{\partial h}{\partial r}+2h=\begin{cases}-0.3784 & \text{for the } M_2\text{-tide,}\\ -0.9481 & \text{for the } O_1\text{-tide.}\end{cases}$$

The mean values of the V5 extension are as follows,

$0.485 \times 10^{-8} \cos(2t - 184.45°)$ on the M_2-tide,
$0.504 \times 10^{-8} \cos(t - 204.84°)$ on the O_1-tide.

Similarly, we obtain the areal strain and its tidal factor by adding the mean of L2+L3 and C1-new as follows,

$$\text{The areal strain} = \begin{cases} 1.043 \times 10^{-8} \cos(2t - 354.04°) & \text{on the } M_2\text{-tide,} \\ 0.471 \times 10^{-8} \cos(t - 359.43°) & \text{on the } O_1\text{-tide.} \end{cases}$$

$$\text{The factor } h - 3l = \begin{cases} 0.4072 & \text{for the } M_2\text{-tide,} \\ 0.4426 & \text{for the } O_1\text{-tide.} \end{cases}$$

Similarly, we obtain the dilatational strain, Δ, from V5+(L2+L3)/2+C1-new, and obtain the tidal factor of the dilataion as follows,

$$\Delta = \begin{cases} 0.573 \times 10^{-8} \cos(2t - 345.23°) & \text{on the } M_2\text{-tide,} \\ 0.217 \times 10^{-8} \cos(t - 273.49°) & \text{on the } O_1\text{-tide.} \end{cases}$$

$$\text{The factor } a\frac{\partial h}{\partial r} + 4h - 6l = \begin{cases} 0.4475 & \text{for the } M_2\text{-tide,} \\ 0.4079 & \text{for the } O_1\text{-tide.} \end{cases}$$

8. Summary

The author has improved some of the extensometers, and has observed the tidal extensions with these instruments in the old Osakayama tunnel since 1947. These instruments are 6 horizontal components of the extensometers, L2, L3, E1, N1, N3 and C1, and 3 vertical components of the extensometers V1, V3 and V5. The 2 horizontal components have been set along the direction of the main tunnel (in S 38° W). The E1 has been set in the east direction, and N1 and N3 have been set in the north direction. C1-old has been set in the passage whose direction is S 52° E which connects the two main tunnels. Afterward, these ends of the C1-old and the N3-old have been kept away from the wall, and have been put on the floor of the tunnel.

From these observations and their tidal analysis, the author obtained the following results.

1) The tidal extension is much amplified in a radius direction of the tunnel. This phenomenon might give advantageous condition for the observations of the tidal strain.

2) The hole effect of the tunnel is not negligible in the C1-old, N3-old and the V3. And the experimental hole effects due to the atmospherical tide have been separated from their global effects on these observations.

3) The vertical, the areal and the dilatational strains have been obtained by use of the components which have few hole effects. And the author has estimated these factors to be, $a\frac{\partial h}{\partial r} + 2h$, $h - 3l$ and $a\frac{\partial h}{\partial r} + 4h - 6l$, respectively.

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