QUANTITATIVE ANALYSIS OF OBSERVED SEISMIC STRAINS IN UNDERGROUND STRUCTURES IN JAPAN

Masahiro NAKAMURA (I)
Shiro IZUMI (II)
Presenting Author: Masahiro NAKAMURA

SUMMARY

A total of 123 seismic records obtained during 91 earthquakes in seven buried pipelines, three submerged tunnels, two embedded tanks and a rock tunnel were analyzed. On average, by assuming the seismic strain of buried pipelines to be unity, those of submerged tunnels and embedded tanks were found to be about 0.39 and 0.14, respectively. By using the fact that the ratio of observed and calculated pipe strain was found to be lognormally distributed, basic information was supplied that can be used to obtain the pipe strain for a given probability of being exceeded.

INTRODUCTION

Past studies have shown that the dynamic responses of buried structures during earthquakes are greatly influenced by the behavior of the surrounding soil (Refs. 1-3). By reflecting the abovementioned finding, the response-displacement method is widely used in Japan for the earthquake resistant design of the structures (Refs. 4-6). However, the distribution of ground displacement during an earthquake, namely the seismic strain in the ground, has not been well understood today. Although the direct measurement of the seismic ground strain is generally difficult, it has been conclusively shown that the buried pipe strains may in most cases be considered to represent the soil strains during an earthquake (Refs. 1 and 7).

In this paper, the seismic strains produced in underground structures are quantitatively investigated by using the data observed at 13 sites from 1970 to 1980. There are 60, 48, 9 and 6 observations for seven buried pipelines, three submerged tunnels, two embedded tanks and a rock tunnel, respectively. The measured pipe strains, which are almost the same as those of the surrounding ground, are investigated in detail. The pipe strains are compared with the calculated strains by three methods. The first method is the Technical Guidance for Petroleum Pipeline, which is frequently used for the earthquake resistant design of buried pipelines in Japan (Ref. 4). The second is the simple method on some assumptions to calculate the seismic ground strains by Rayleigh wave propagation (Ref. 8). The third is the statistical method, which is often referred to as the Type I Quantification Analysis in Japan (Ref. 9).

OBSERVED SEISMIC STRAINS IN UNDERGROUND STRUCTURES

Table 1 shows the list of the observation sites, types of structures and their relevant properties. The epicenters, depths and magnitudes of the 91

(I) Chief Engineer, Technical Research Institute, Fujita Corp., Yokohama, Japan (II) Deputy Manager, Civil Engineering Admin. Dept., Fujita Corp., Tokyo, Japan

earthquakes and the complete information of the 123 data are summarized in Ref. 7. Figure 1 shows the cumulative frequency distributions of observed strains ε for the four different types of structures. The strain ε indicates the longitudinal axial strain for linear structures and the horizontal circumferential strain for embedded tanks. It is clearly seen that the observed strains are the smallest for the rock tunnel and the largest for the buried pipelines. To examine the effect of acceleration levels and ground conditions on seismic strains, the cumulative frequency distributions of $\varepsilon/(a \cdot T/2\pi)$ are plotted in Fig. 2, where a and T are the measured peak acceleration and the natural period of the ground, respectively. The period T is estimated by Eq. 1 using the thickness H_i and shearing wave velocity V_{si} of each layer.

$$T = 4\ \Sigma\ (H_i/V_{si}) \qquad (1)$$

The seismic strain generally increases in the following order: embedded tanks, rock tunnels, submerged tunnels and buried pipelines. While the rock tunnel gave the smallest strain in Fig. 1, the smallest strain in Fig. 2 corresponds to the embedded tank. This change has probably resulted from the fact that, while the strain in the rock tunnel is almost the same as that in the surrounding rock, the strain in the embedded tank is considerably smaller than that in the surrounding ground (Ref. 3). At the 50%-level of the cumulative frequency distribution in Fig. 2, the ratios among the strains of pipeline, submerged tunnel and embedded tank are 1:0.39:0.14. Measured axial strains ε of pipes and tunnels are shown in Fig. 3 for the four different groups of earthquake magnitude ($M \geq 7$, $7 > M \geq 6$, $6 > M \geq 5$ and $5 > M$) plotted against the epicentral distance. It is interesting to notice that the slope of the regression line for $M \geq 7$ is smaller than those for $7 > M \geq 6$ and $6 > M \geq 5$. This seems to indicate that the strains caused by large earthquakes do not decrease rapidly with the increase in epicentral distance.

SEISMIC STRAINS IN BURIED PIPELINES

The observed axial pipe strains ε are plotted against the peak accelerations a for the four different groups of earthquake magnitudes ($M \geq 7$, $7 > M \geq 6$, $6 > M \geq 5$ and $5 > M$) in Fig. 4. The four lines in this figure are the regression lines shown in Eq. 2, which are obtained from each magnitude group (Ref. 7).

$$\log \varepsilon = \alpha + \beta \cdot \log a \qquad (2)$$

It can be easily seen in Fig. 4 that the earthquakes with larger magnitude tend to produce higher axial pipe strains for the same acceleration level than those with smaller magnitude do. The value of the parameter β in Eq. 2 is found to increase to 1 with earthquake magnitude. The correlation between ε and a is again examined in Fig. 5 for the two groups of data classified according to the epicentral distance Δ. The observed data were divided into two groups with $\Delta < 150$km and $\Delta \geq 150$km. It can be easily seen in Fig. 5 that the earthquakes with longer epicentral distances tend to produce higher axial pipe strains for the same acceleration level than those with shorter distances do. The value of the parameter β in Eq. 2 is found to increase to 1 with epicentral distance. However, the data with epicentral distance equal to or greater than 150km generally include almost of the data with large earthquake magnitudes.

The axial pipe strains are plotted again in Fig. 6 against $a \cdot T/2\pi$ in order to approximately take into account the effect of ground condition. The coefficients of correlation γ are found to be much higher than those obtained in Fig. 4, indicating that the axial pipe strains are more strongly correlated to the ground velocity than to the ground acceleration. In especial, the coefficient of correlation γ is as high as 0.944 for $M \geq 7$. The parameter β of the regression line increases to 1 with the earthquake magnitude. On the occasion of the regression line with $M \geq 7$, since β is nearly equal to 1, the axial pipe strain is in direct proportion to the parameter $a \cdot T/2\pi$. There are 17 observed strain data for which the ground velocities were also measured. Figure 7 shows the data observed at 2 sites (Shimonaga and Kansen in Table 1) against the measured longitudinal peak velocity v. The high value of $0.934 \geq \gamma \geq 0.876$ clearly indicates the strong correlation between the axial pipe strain and the velocity. Since the parameter β of each regression line is nearly equal to 1, the axial pipe strain is in direct proportion to the velocity and the regression line between the strain ε and the velocity v in Eq. 2 is shown in Eq. 3.

$$\varepsilon = 10^{\alpha} \cdot v \qquad (3)$$

The ground strain in the axial direction of wave propagation is directly proportional to the velocity v of ground movement, and inversely proportional to the wave propagation speed C through ground (Ref. 10). Assuming the parameter 10^{α} to be equal to $(1/C)$ in Eq. 3, the calculated values of wave velocity C at Kansen and Shimonaga site are 2200m/s and 1000m/s, respectively.

COMPARISON BETWEEN OBSERVED AND CALCULATED STRAINS

The calculated strains are e_{RT} and e_{RG} by the Technical Guidance for Petroleum Pipeline (Ref. 4), e_P by the method proposed by the authors (Ref. 8) and $\bar{\varepsilon}$ by the Type I Quantification Analysis (Ref. 9). Let the ratio of an observed strain ε and the calculated strain e be denoted by S $(=\varepsilon/e)$. The χ^2 goodness-of-fit test was applied to the values of S by assuming the lognormal distribution with the mean and variance of the data S. It may be concluded that the data are not in significant contradiction to the lognormal model at 5% significance level. Figure 8 shows the lognormal distribution curves for the four different types of calculated strains. The means of ε/e_{RT}, ε/e_{RG}, ε/e_P and $\varepsilon/\bar{\varepsilon}$ are 0.315, 0.504, 0.922 and 1.29, respectively. The variances of those are 0.133, 0.352, 1.20 and 1.77, respectively. The values of probability p, for which the observed strain ε is smaller than the calculated strain e, are 96%, 88%, 71% and 55% for e_{RT}, e_{RG}, e_P and $\bar{\varepsilon}$, respectively. Moreover, if S is assumed to be lognormally distributed, the value of S for a specified probability of being exceeded, p, can be easily evaluated. Such values of S for p=0.01, 0.05, 0.10, 0.50 are given in Table 2. When the calculated strain is combined with the factors given in Table 2, a buried pipe strain for a given probability of being exceeded may be constructed.

CONCLUSIONS

In this paper, seismic strains observed in several kinds of underground structures were investigated, and the strains calculated by the three methods were compared with the observed pipe strains. Major points of interest found from the study are summarized below.

(1) The level of the normalized seismic strains $\varepsilon/(a\cdot T/2\pi)$ generally differs according to the different types of underground structures. Supposing that the normalized strain in a buried pipeline is 1, those in a submerged tunnel and an embedded tanks are 0.39 and 0.14, respectively.

(2) The decrease of the seismic strain in buried linear structures with epicentral distance is slower for large magnitude earthquakes than for smaller earthquakes.

(3) For the same level of the peak acceleration (or velocity), the seismic strain of a buried pipeline increases with the earthquake magnitude and the epicentral distance.

(4) The axial pipe strain ε is more strongly correlated with the velocity v or $(a\cdot T/2\pi)$ than with the acceleration a.

(5) The pipe strain ε is directly proportionate to a^{β} (where $0.4\leq\beta\leq 1$). The value of β approaches to 1 as the earthquake magnitude and the epicentral distance increase.

(6) The pipe strain ε is directly proportionate to the ground velocity v, and to the parameter $(a\cdot T/2\pi)$ for $M\geq 7$ earthquakes.

(7) By using the fact that the ratio of observed and calculated strain was found to be lognormally distributed, basic information was supplied that can be used to obtain the pipe strain for a given probability of being exceeded.

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REFERENCES

(1) Sakurai A., T.Takahashi, H.Tsutumi, H.Yajima, T.Noguchi and T.Iwakata: Dynamic stresses of underground pipelines during earthquakes, Report No.67058, Central Research Institute of Electric Power Industry, 1967. (2) Tamura C., S.Okamoto and M.Hamada: Dynamic behavior of a submerged tunnel during earthquakes, Report of Institute of Industrial Science, University of Tokyo, Vol.24, No.5, 1975. (3) Hamada M.: Basic investigation on dynamic behavior of a large-scale embedded tank during earthquakes, Thesis of University of Tokyo, 1979. (4) Ministrial notification on details of engineering requirements for oil pipeline enterprise, Notification No.1 of Ministry of International Trade and Industry, Ministry of Transport, Ministry of Construction and Ministry of Autonomy, 1973. (5) Earthquake resistant design guidance for submerged tunnel (proporsal), JSCE, 1975. (6) Technical guidance for underground storage facilities (proposal), JSCE, 1980. (7) Nakamura M., T.Katayama and K.Kubo: Quantitative study on observed seismic strains in underground structures, Proceedigs of JSCE, No.320, 1982. (8) Nakamura M., B.Hashimoto: A simple method of calculation to estimate strains in ground during earthquake by theory of elastic wave propagation, Report of Science and Engineering Research Laboratory, Waseda University, No.92, 1980. (9) Nakamura M.: Estimation of seismic ground strain by quantitative analysis of observed strains in underground structures, Proceedings of the Sixth Japan Earthquake Engineering Symposium, 1982. (10) Newmark, N.M.: Problems in wave propagation in soil and rock, International Symposium on Propagation and Dynamic Properties of Earth Materials, 1967.

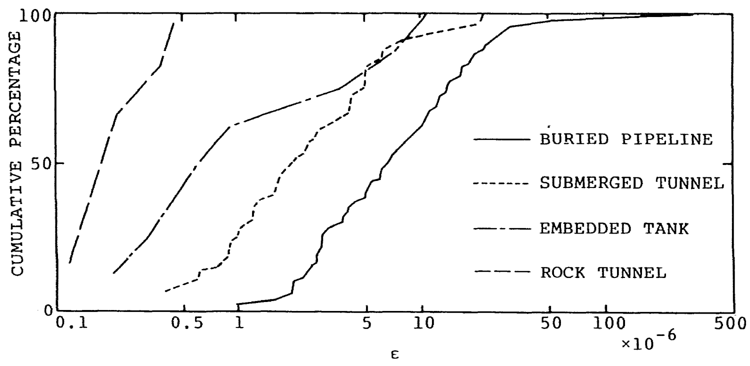

Fig. 1 Cumulative Frequency Distribution Curves for ε.

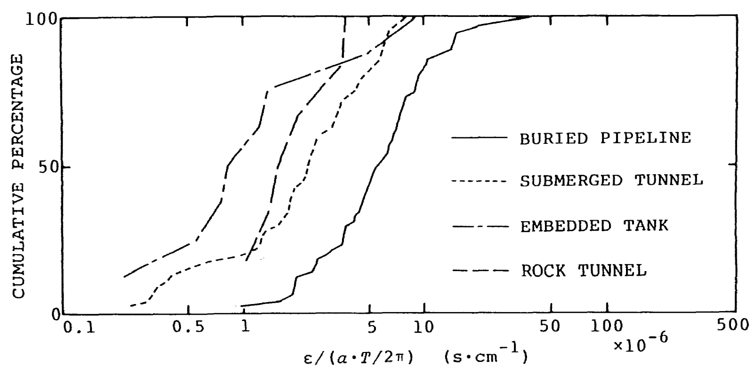

Fig. 2 Cumulative Frequency Distribution Curves for $\varepsilon/(a \cdot T/2\pi)$.

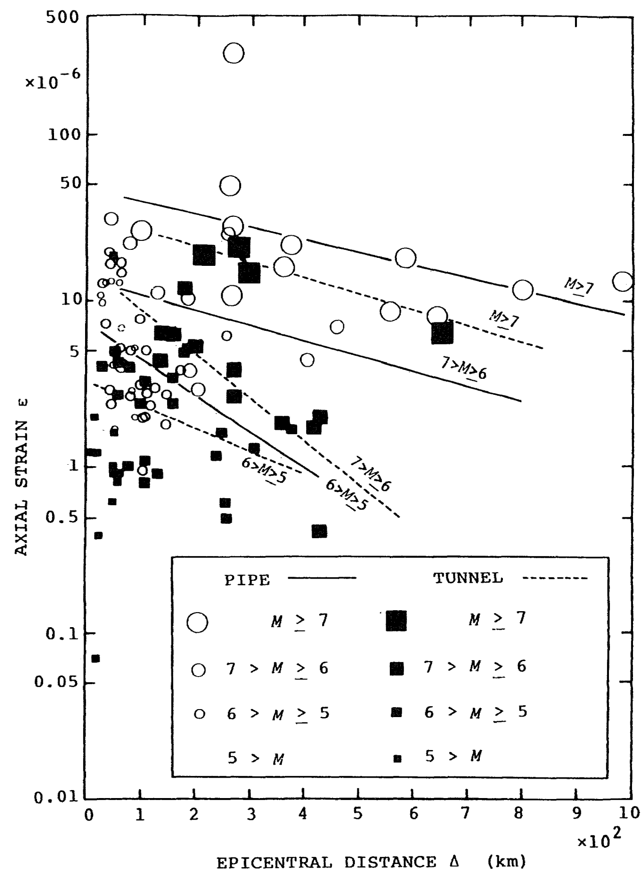

Fig. 3 Relation between Axial Strain and Epicentral Distance for Linear Underground Structures.

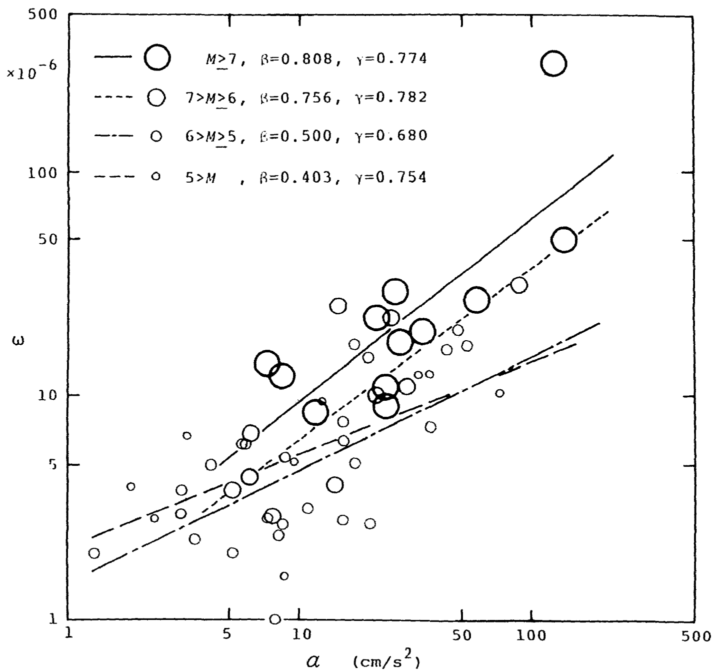

Fig. 4 Relation between Axial Pipe Strain and Longitudinal Peak Acceleration.

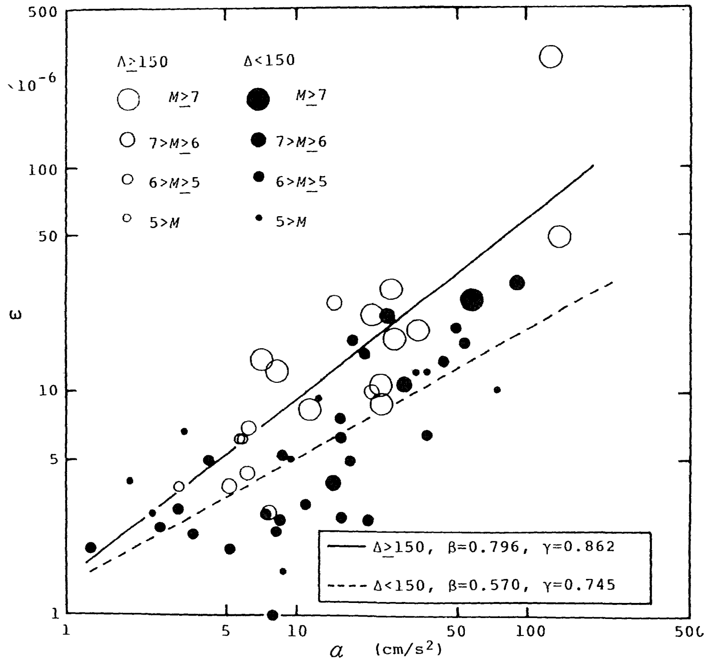

Fig. 5 Relation between Axial Pipe Strain and Longitudinal Peak Acceleration (Δ<150km and Δ≥150km).

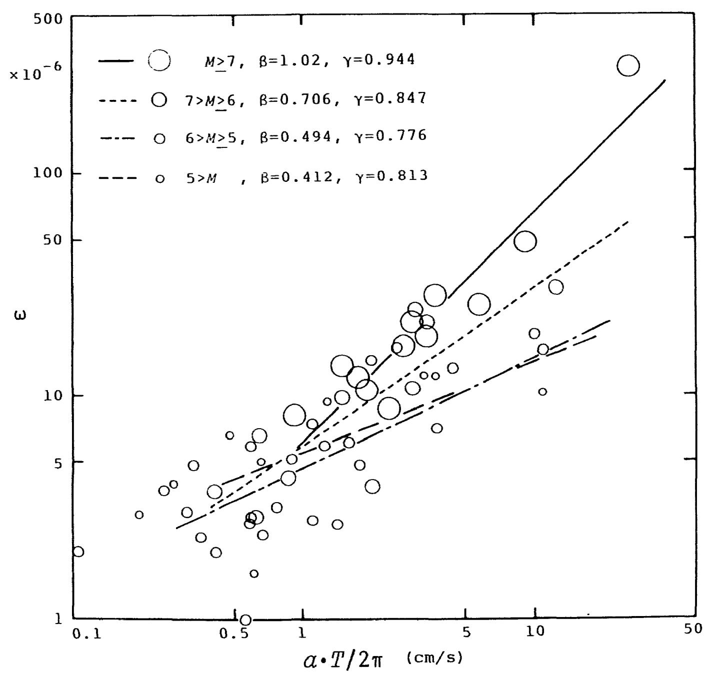

Fig. 6 Relation between Axial Pipe Strain and $a \cdot T/2\pi$.

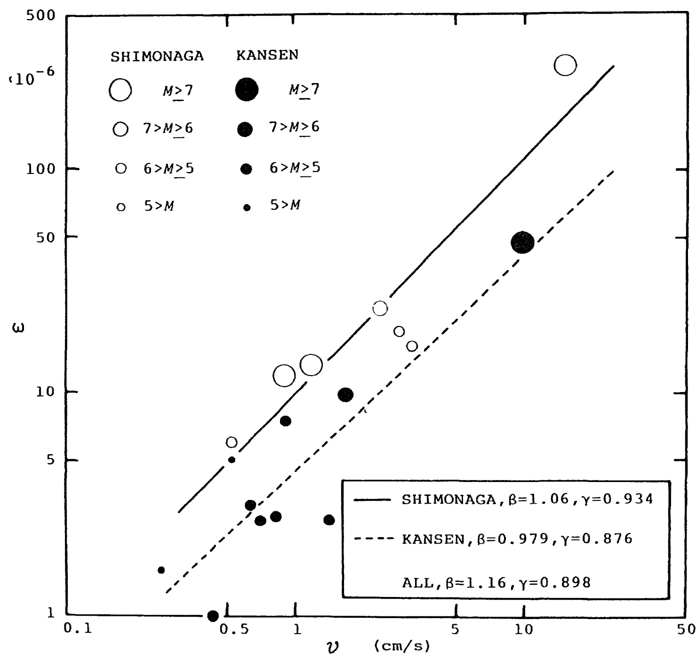

Fig. 7 Relation between Axial Pipe Strain and Peak Velocity v.

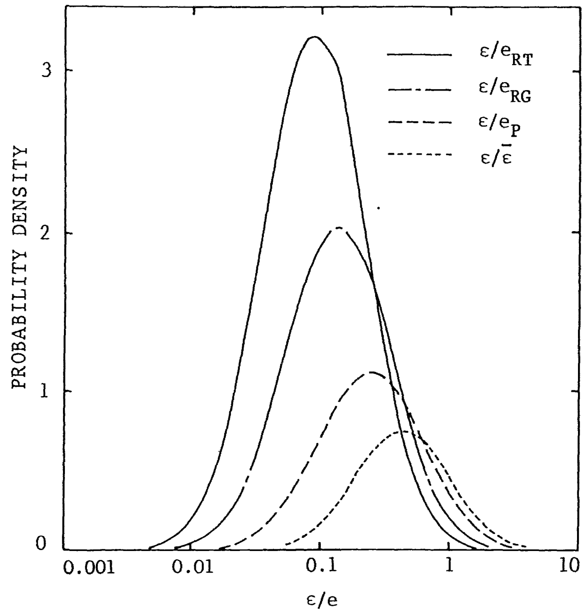

Fig. 8 Probability Density Functions of ε/e (=Measured/Estimated).

Table 1 Observation Sites and Types of Underground Structures.

NO.	SITE	STRUCTURE	T (sec)	DIAMETER (mm)	THICKNESS (mm)
1	YOKOHAMA	PIPE	0.914	165.2	5.0
2	SOKA	PIPE	0.644	406.4	7.9
3	OMORI	PIPE	0.632	216.3	5.8
4	KANSEN	PIPE	0.437	1554.0	18.0
5	SHIMONAGA	PIPE	1.310	1041.0	13.0
6	HACHINOHE	PIPE	0.504	1219.2	16.0
7	MINAMIWATARIDA	PIPE	0.878	1838.0	19.0
8	HANEDA	TUNNEL	1.600	—	—
9	KINUURA	TUNNEL	0.969	—	—
10	OGISHIMA	TUNNEL	1.220	—	—
11	NEGISHI	TANK	0.294	—	—
12	SHIMIZU	TANK	1.020	—	—
13	ISHIZUKAYAMA	ROCK TUNNEL	0.229	—	—

Table 2 Value of ε/e for Specified Probabilities of Being Exceeded.

ε/e	MEAN	VARIANCE	VALUE OF ε/e CORRESPONDING TO p			
			p=0.01	p=0.05	p=0.10	p=0.50
ε/e_{RT}	0.315	0.133	1.76	0.93	0.67	0.21
ε/e_{RG}	0.504	0.352	2.87	1.51	1.08	0.33
ε/e_{P}	0.922	1.20	5.29	2.77	1.97	0.59
$\varepsilon/\bar{\varepsilon}$	1.29	1.77	6.53	3.63	2.67	0.90