Influence of Soils on Impact Parameters of Seismic Effect

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***Abstract*—The aim of the article is to study the influence of the propagation velocity of longitudinal V_p and transverse V_s waves, as well as the density ρ of soil, on the real seismic effects parameters: intensity, peak acceleration, frequency. To achieve this goal, the Geophysical Institute of the VSC RAS developed a database containing 63478 three-dimensional records of earthquakes from 11/05/1996 through 31/12/2017, including all KNET records with epicentral distance up to 50 km and intensity above 0.5 JMA. The records were amiably provided for non-commercial use by the KNET system. In the database V_p, V_s, ρ are contained in the form of tables and graphs of the stations soils down to depth of 20 m. We considered the intervals of epicentral distances of 0-10, 5-15, 10-20, 15-25, 20-30, 35-45, 40-50 km and determined the mean values of V_p, V_s, ρ and seismic parameters for different magnitudes in these intervals: M>6, 5<M<6, 4<M<5, M<4. Based on the distribution histograms of the mean values of V_p, V_s, ρ, the entire range of V_p, V_s, ρ was divided into four intervals with an equal number of samples in each interval. The limits of the four intervals were determined according to the calculation of the median, lower and upper quartiles. It is shown that for soils with high values of V_s the intensities significantly decrease in comparison with soils with low propagation velocity of transverse wave at epicenter distances less than 50 km and magnitudes less than 6. For magnitudes over 6, this effect is not statistically significant due to the insufficient number of records at small epicentral distances. It is shown that during comparison of two soils, one V_s>244 m/s and another V_s<244 m/s, the *PHA* is 5-10 gal above on soils with high V_s ceteris paribus, while $p<0.05$. The study of *PVA* showed that V_s does not affect peak vertical acceleration with $p<0.05$. For soils with different V_p values, the intensity on soils with high V_p values is significantly lower than on soils with low V_p values. Note that this effect does not occur for events with high magnitudes greater than 6, where confidence intervals overlap due to a small number of recorded events. The results showed that for soils with high and low V_p values, the difference between the average *PHA* and *PVA* values between soils with different V_p values is not reliable ($p>0.05$) for all magnitude ranges and for epicentral distances not exceeding 50 km.**

Keywords—strong motions database; earthquake; epicentral distance; P-wave velocity; S-wave velocity; intensity; peak vertical acceleration; peak horizontal acceleration

I. INTRODUCTION

Even when the Geophysical Institute was established, the idea of development of database of three-dimensional records of real seismic events was put forward [1; 4; 5-13] to study the relationship between the parameters of seismic motions and soil properties. It was planned that the database will contain the standard characteristics of the earthquake, the characteristics of seismic effects recorded by the instruments at the seismic station, the parameters of the station location and the distribution of soil characteristics in depth. The work has been carried out for a several years and now the

Geophysical Institute has created a strong motions database [3], which is updated annually.

Recently, much attention is paid to the study of variations in the propagation velocities of the longitudinal (V_p) and transverse (V_s) seismic waves, as well as their ratio (V_p/V_s). The research is carried out by means of three-dimensional seismic tomography [14]. The study of the variations of V_p, V_s and V_p/V_s allows to judge about the presence of underground magmatic material, water, etc.

We also investigated the influence of soil properties such as: V_p, V_s, V_p/V_s, ρ on the parameters of seismic activity of a given area. A sample of the strong motions database developed by one of the co-authors at the Geophysical Institute of VSC RAS is used [3]. The sample contains 63478 records from 11/05/1996 to 31/12/2017, among them all KNET records with epicentral distance up to 50 km with intensity over 0.5 JMA (2.17 MSK). The records were amiable provided for non-commercial use by the KNET system [2].

II. Strong Motions Database

In our database, the values V_p, V_s, V_p/V_s and ρ are presented in the form of tables and graphs on the soils of stations up to 20 m depth. For the study we used the average values of V_p, V_s, V_p/V_s and ρ for each soil, which were calculated to a depth of 20 m. In the present article it was considered that the last value of V_p, V_s, V_p/V_s and ρ corresponds to the base of the soil, and this value extended to a depth of 20 m. The spread of data and the error in determining the mean are large enough. For example, for the soil of the station AIC006, the average values, standard deviation and standard error of mean are shown in Table I.

TABLE I. Descriptive Statistics V_P, V_S, V_P/V_S, P

No.	Parameter	Mean	Standard deviation	Standard error of mean
1	Vp. m/s	1529	434.0	99.6
2	Vs. m/s	261	121.5	27.9
3	Vp/Vs	5.866	4.7780	0.9238
4	ρ. tons/m3	2.080	0.1218	0.0279

The parameters of seismic event manifestation were calculated by the authors on the basis of instrumental records of the created database [3]. The calculations were carried out in the statistical system "Statistica-13". Means, minimum and maximum values, standard deviations and standard error of mean were investigated of the following parameters: peak acceleration, the frequency of the Fourier spectrum maximum, mean frequency of the Fourier spectrum, frequency shift (difference between the frequency of the Fourier spectrum maximum and mean frequency of the Fourier spectrum) – for vertical and horizontal components; epicentral distance, intensity, hypocentral distance, V_p, V_s, ρ, the ratio of peak vertical to peak horizontal acceleration. The tests of normality (*Normal expected frequencies, Kolmogorov-Smirnov & Lilliefors test, and Shapiro-Wilk's W test*) showed the normality of the sample for the presented components – so it is possible to carry out valuable statistical studies.

III. Research Methods

We used the statistical system "Statistica-13". Investigation of the dependencies of seismic intensity, peak accelerations, the frequency of the Fourier spectrum maximum, frequency shift (for horizontal and vertical components) at the epicentral distance at different magnitudes were realized. A sample for epicentral distances up to 50 km was investigated.

Intervals of epicentral distances (0-10, 5-15, 10-20, 15-25, 20-30, 25-35; 30-35; 35-45, 40-50 km) were considered and the means for different magnitudes (M >6, 5< M <6, 4<M<5, M <4) were determined in these intervals.

We divided the range of values of V_s, V_p, V_p/V_s, ρ into four intervals with equal number of counts in each interval. The first interval - less than lower quartile, the second – from lower quartile to median, the third – from median to upper quartile and the fourth – more than upper quartile.

IV. Influence of The S-Wave Propagation Velocity in Soils on Impact Parameters

A. Intensity

On average, for any magnitudes, V_p, V_s, ρ the dependence of intensity on the epicentral distance has the form shown in Fig. 1, where mean intensity values (Mean) in the intervals of epicentral distance, mean values ± standard error of mean (Mean ± S. E.), linear trend of mean (Linear (Mean)) are presented. The similar results in the form of figures and tables were obtained for magnitudes in intervals: >6, 5 ÷ 6, 4 ÷ 5, <4; and V_s: 81 m/s ÷ 244 m/s, 244 m/s ÷ 341 m/s, 341 m/s ÷ 447 m/s, 447 m/s ÷ 1700 m/s. From this figure we can draw quite obvious conclusion that the intensity near the epicenter is usually higher than with the distance from it. The intensity dependence on the epicentral distance is close to linear with R^2 around 0.86.

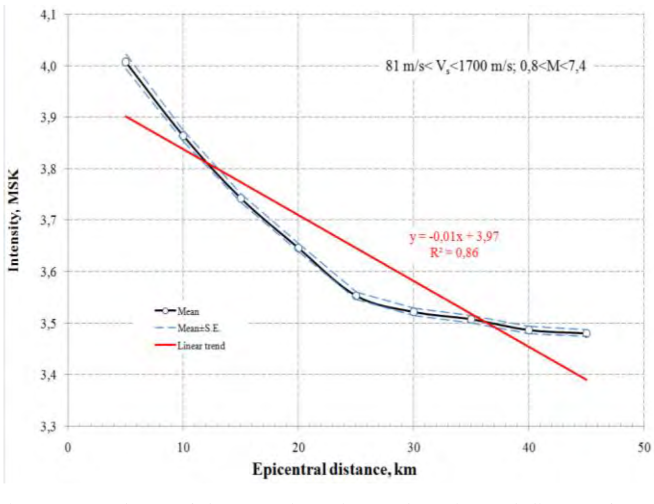

Fig. 1. Dependence of the mean intensity on the epicentral distance for any magnitudes, V_p, V_s, ρ.

The intensity dependence on the epicentral distance at different magnitudes for V_s from 81 m/s to 244 m/s is shown in Fig. 2.

The similar results in the form of figures and tables were obtained for V_s: 81 m/s÷1700 m/s, 244 m/s÷341 m/s, 341 m/s÷447 m/s, 447 m/s÷1700 m/s. Fig. 2 shows that an increase in the event magnitude leads to an increase in the impact intensity, except the case of high magnitudes M>6, when the mean intensity falls at small epicentral distances. It is connected with the small number of events with large magnitudes recorded in the database. Calculations show that the confidential intervals of intensity for small epicentral distances (0-10 km) increase; for soils with a low value of V_s<244 m/s the intensity is equal to 7.39±1.01; number of cases N=4 and at a distance of 40-50 km the confidential intervals are narrowed and the intensity is equal to 6.56±0.18; N=51. If we consider soils with high V_s>447 m/s then the intensity is 8.12±0.66; N=7 for epicentral distances 0-10 km. Confidential intervals for intensity at small epicentral distances are coincided for soils with low and high V_s. Whence it follows that the difference in intensity is not significant, due to the insufficient number of records at small epicentral distances.

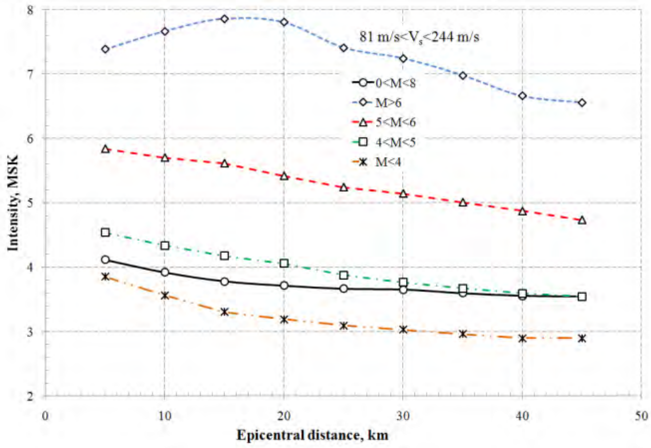

Fig. 2. Dependence of mean intensity on epicentral distance, soils: 81 m/s< V_s <244 m/s

TABLE II. VALUES OF MEAN INTENSITY ± STANDARD ERROR OF MEAN AND NUMBER OF CASES (N) IN THE EPICENTRAL DISTANCES INTERVALS FOR DIFFERENT VS IN THE FULL RANGE OF MAGNITUDE CHANGE

V_s, m/s		81-1700	81-244	244-341	341-447	>447
Epicentral distances, km	0-10	4.008±0.014; N=5414	4.118±0.023; N=1673	4.214±0.032; N=1138	3.972±0.030; N=1322	3.702±0.028; N=1247
	5-15	3.864±0.010; N=9143	3.922±0.020; N=2429	3.964±0.021; N=2182	3.889±0.022; N=2218	3.672±0.019; N=2204
	10-20	3.742±0.008; N=11997	3.782±0.016; N=3312	3.795±0.016; N=3073	3.729±0.018; N=2791	3.643±0.017; N=2691
	15-25	3.646±0.007; N=13582	3.717±0.015; N=3735	3.661±0.015; N=3322	3.614±0.016; N=3200	3.570±0.016; N=3231
	20-30	3.553±0.007; N=14361	3.668±0.016; N=3327	3.573±0.015; N=3508	3.532±0.015; N=3455	3.440±0.013; N=3937
	25-35	3.521±0.007; N=14787	3.651±0.016; N=3248	3.590±0.014; N=3717	3.497±0.014; N=3612	3.363±0.012; N=4074
	30-40	3.508±0.007; N=14906	3.596±0.015; N=3569	3.582±0.014; N=3803	3.486±0.014; N=3681	3.363±0.013; N=3779
	35-45	3.486±0.006; N=16047	3.555±0.014; N=3769	3.551±0.013; N=4089	3.479±0.012; N=4194	3.355±0.013; N=3931
	40-50	3.480±0.006; N=16747	3.546±0.014; N=3869	3.537±0.013; N=4040	3.498±0.012; N=4577	3.339±0.012; N=4175

Statistical analysis has shown that for soils with high S-wave propagation velocities (V_s>447 m/s) the intensities fall significantly in comparison with soils with low S-wave propagation velocities (V_s <244 m/s), which can be understood from Table II.

B. *Peak horizontal and vertical accelerations PHA, PVA.*

Mean values of *PHA* and *PVA* in the four intervals of V_s the values are in the Table III.

The mean peak horizontal acceleration *PHA* is approximately 2.2 times higher than *PVA* on the same soils (Table III), and *PHA* on soils with low V_s (<244 m/s) is significantly lower (p<0,05) than on soils with high V_s (>244 m/s). To explore this effect, the *PHA* dependence on the epicentral distance on soils with different V_s values was tested. Fig. 3 shows the dependence of *PHA* on the epicentral distance for all magnitudes.

TABLE III. MEAN VALUES ± STANDARD ERROR OF MEAN FOR DIFFERENT VS IN THE FULL RANGE OF MAGNITUDE CHANGE

Vs, m/s	81-244	244-341	341-447	>447
Vs, m/s	190.66±0.3	285.88±0.22	392.11±0.26	612.01±1.98
INT, MSK	3.7±0.01	3.66±0.01	3.58±0.01	3.45±0.01
PHA, gal	19.7±0.3	23.17±0.36	22.94±0.37	23.61±0.34
PVA, gal	9.18±0.13	10.78±0.17	10.01±0.16	9.19±0.14

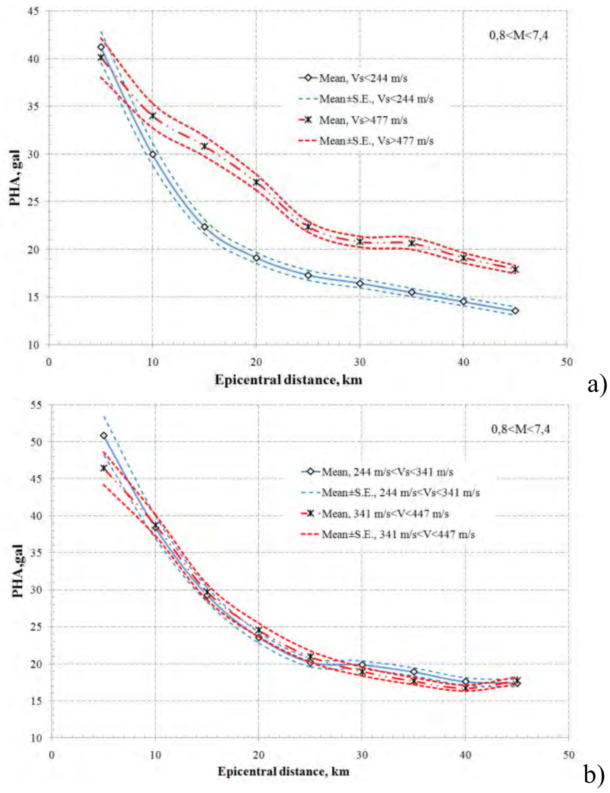

Fig. 3. Dependence of the *PHA* on the epicentral distance for V_s<244 m/s and V_s>447 m/s (a); for 244 m/s<V_s<341 m/s, and 341 m/s<V_s<447 m/s (b)

It can be seen that for the entire range of magnitudes the mean *PHA* values for soils with high V_s values (>447 m/s) are significantly higher than for soils with low V_s values (<244 m/s) for epicentral distances from 10 to 50 km. For the epicentral distance from 0 to 10 km the difference between similar *PHA* values is not significant, as shown in Fig. 3 (*PHA*=40,1±2,1) for all magnitudes. For V_s values from 244 m/s to 341 m/s and from 341 m/s to 447 m/s, the difference between *PHA* averages is not significant (Fig. 3). So, the difference between average *PHA* values for V_s values above 244 m/s is negligible at epicentral distance values above 15 km. The difference between average *PHA* values for V_s values below and above 244 m/s is significant for epicentral values above 15 km. At comparison of two soils, in one of which S-wave propagation velocity exceeds 244 m/s, and the other less than 244 m/s, the *PHA* is 5-15 gal higher on soils with high V_s, ceteris paribus, with $p<0.05$.

At magnitude M<6 dependence of the *PHA* on the epicentral distance is very similar to Fig. 3, while, for M>6 the difference between the mean values of *PHA* dependence is not significant, although the acceleration can exceed 500 gal.

The study of *PVA* value behavior showed that such a characteristic of soil as V_s does not affect the peak vertical acceleration with $p<0.05$.

It was also studied the ratio *PVA/PHA* (Fig. 4). The results of study showed that the *PVA/PHA* ratio is lower on soils with high V_s than on soils with low V_s. For magnitudes above 5, the difference in *PVA/PHA* for soils with high and low values of V_s is not statistically significant. It was also found that as the magnitude increases, the *PVA/PHA* ratio decreases significantly for soils with a low V_s value, while on soils with a high V_s magnitude value does not affect *PVA/PHA*.

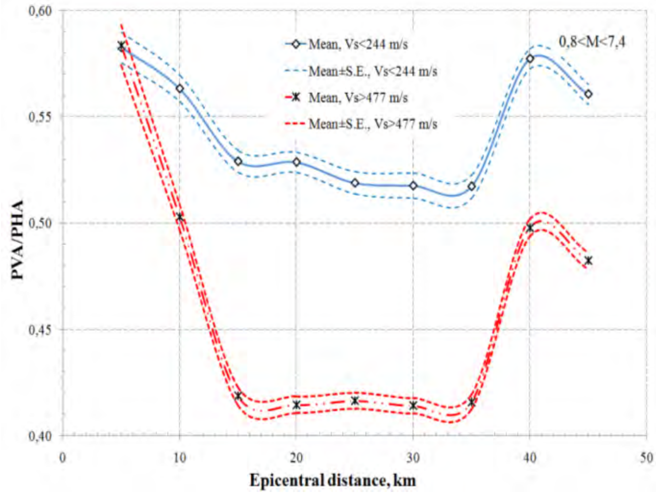

Fig. 4. The dependence of *PVA/PHA* on the epicentral distance for soils with different V_s.

V. INFLUENCE OF THE P-WAVE PROPAGATION VELOCITY IN THE SOIL ON IMPACT PARAMETERS

A. Intensity

For mean values (Table IV) in four V_p intervals, *INT*, V_p, *PHA* and *PVA* values are:

TABLE IV. VALUES OF MEAN INTENSITY ± STANDARD ERROR OF MEAN IN THE EPICENTRAL DISTANCES INTERVALS FOR DIFFERENT VP IN THE FULL RANGE OF MAGNITUDE CHANGE

Vp, m/s	**<1271**	**1271 - 1467**	**1467 - 1684**	**>1684**
INT, MSK	3.7±0.01	3.59±0.01	3.57±0.01	3.53±0.01
Vp, m/s	1050.63±1.60	1383.60±0.44	1571.12±0.54	2037.96±3.40
PHA, gal	23.09±0.34	20.54±0.32	22.11±0.38	23.64±0.32
PVA, gal	10.59±0.16	9.65±0.15	9.65±0.17	9.24±0.13

From Table IV it follows that the mean intensity of impact is significantly lower on soils with high values of V_p.

In Fig. 5 it is possible to compare the results of calculations of the soils influence with different V_s and V_p on the mean intensity across the full range of magnitude.

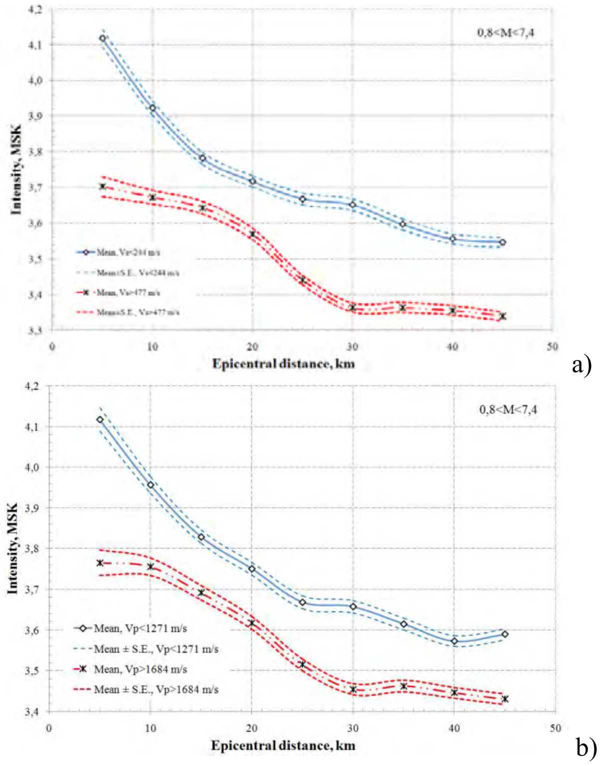

Fig. 5. The dependence of the mean intensity on the epicentral distance for soils with different V_s. (a); with different V_p (b)

Intensity values in Fig. 5a in the range of epicentral distances 0-50 km are between the curve corresponding to the soil with a high velocity of S-waves - V_s>447 m/s and the curve corresponding to the soil with a low speed - V_s<244 m/s. A similar pattern is observed for the velocity of P-waves (Fig. 5b), with the difference that the intensity values are limited between the curve with V_p>1467 m/s and the curve with V_p<1271 m/s. There is a significant increase in the average intensity for soils with low values V_s and V_p and vice versa: there is a significant decrease in the average intensity for soils with high values V_s and V_p. Similar calculations were made for soils with different values of V_p and for intervals of magnitudes: >6, 5 ÷ 6, 4 ÷ 5, <4. The results showed that the intensity on soils with high V_s and V_p values was significantly lower than on soils with low V_s and V_p values. Note that this effect does not occur for events with high magnitudes greater than 6, where confidence intervals overlap due to a small number of recorded events.

B. PHA, PVA

In the full range of magnitudes, the mean peak horizontal acceleration *PHA* is approximately 2.2 times higher than *PVA* on the same soils (Table IV). There is a significant increase in the mean value of *PVA* on soils with low V_p. The difference in mean *PHA* values on soils with different V_p is insignificant.

A detailed study of the *PHA* dependence on the epicentral distance on soils with different V_p values considering events with different magnitudes was carried out. The results showed that the difference between the mean *PHA* and *PVA* values between soils with different V_p values is not significant ($p>0.05$) for all ranges of magnitude change and for epicentral ones not exceeding 50 km. The corresponding graphs and tables are not given in the article in order to not to clutter the text, but they are available from the authors.

VI. Conclusion

1. The study used a sample from the Strong Motions Database of the Geophysical Institute of the VSC RAS containing 63478 three-dimensional records of earthquakes from 11/05/1996 to 31/12/2017, including all KNET records with an epicentral distance up to 50 km with an intensity above 0.5 JMA. The sample contains the propagation velocity of S- and P-waves, density in the soils of the stations up to 20 m depth, as well as the calculated parameters of the seismic event at the station.
2. We considered the intervals of epicentral distances of 0-10, 5-15, 10-20, 15-25, 20-30, 35-45, 40-50 km and determined the mean values of V_p, V_s, ρ and seismic parameters for different magnitudes M>6, 5<M<6, 4<M<5, M<4 in these intervals. Based on the distribution histograms of the mean values of V_p, V_s, ρ, the entire range of V_p, V_s, ρ was divided into four intervals with an equal number of samples in each interval. The limits of the four intervals were determined according to the calculation of the median, lower and upper quartiles.
3. It is shown that for soils with high values of V_s intensity fall significantly compared to soils with low S-wave propagation velocities at epicentral distances of less than 50 km and magnitudes of less than 6. For magnitudes greater than 6, such effect is not statistically significant due to the insufficient number of records at small epicentral distances. It is shown that when comparing two soils, in one V_s>244 m/s, and in the other V_s<244 m / s, the *PHA* is 5-10 gal higher on soils with high V_s, ceteris paribus with $p<0.05$. The study of *PVA* behavior showed that such soil characteristic as V_s does not affect the peak vertical acceleration with $p<0.05$.
4. For soils with different V_p values, the intensity on soils with high V_p values is significantly lower than on soils with low V_p values. Note that this effect does not occur for events with high magnitudes greater than 6, where confidence intervals overlap due to a small number of reported events. The results showed that for soils with high and low V_p values, the difference between the average *PHA* and *PVA* values between soils with different V_p values is not significant ($p>0.05$) for all ranges of magnitude change and for epicentral distances not exceeding 50 km.
5. The influence of V_p/V_s, ρ on the parameters of the real seismic effect and the nature of the dependence of the frequency characteristics on V_s, V_p, V_p/V_s, ρ will be considered in our next articles.

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